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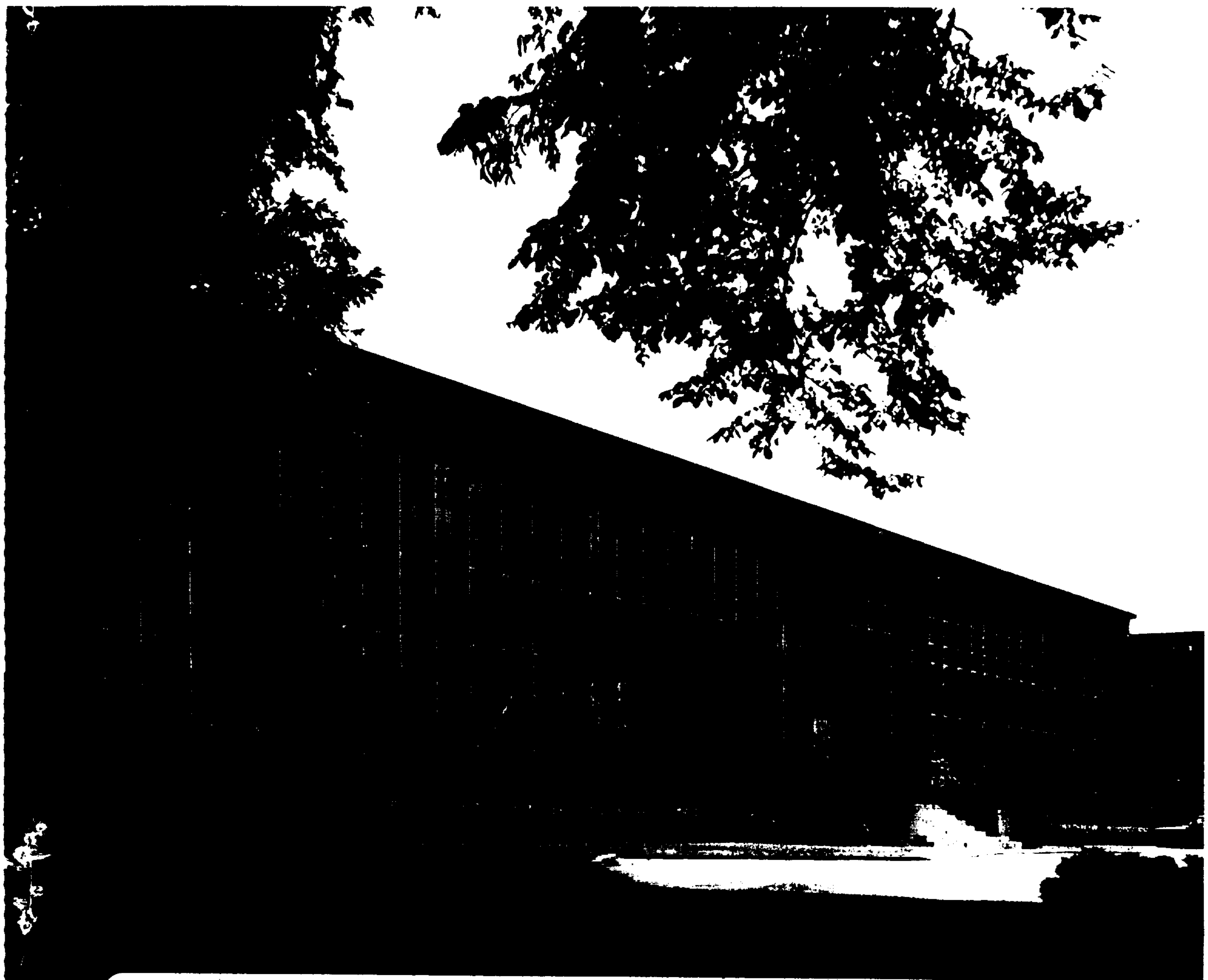

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MRI

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Midwest Research Institute is an independent, not-for-profit organization that performs and manages research and development programs for clients in business, industry, government, and for other public and private sector groups. Founded in 1944 by a group of Midwestern civic, business, and technical leaders, MRI has become one of the nation's leading independent research institutes.

Research Activities

MRI research projects vary in size and scope, ranging from economic development studies for individual rural communities to long-term projects for the EPA requiring the supervision of subcontractors and management of complex data bases. Over 1,000 MRI research and support staff carry out programs in the areas of environment and health, materials and process development, economics and management sciences, and solar energy. The new MRI Center for Advanced Instrumentation for Environmental and Health Research houses the most advanced analytical instrumentation in the midcontinent region, signifying MRI's commitment to solving some of the most threatening problems of the day.

Locations

Kansas City, Missouri, is the home of Midwest Research Institute's headquarters and main laboratories. MRI also has offices in the Raleigh, North Carolina, and the Washington, D. C., areas. The national Solar Energy Research Institute in Golden, Colorado, is managed and operated by MRI, under contract to the Department of Energy. MRI has conducted research for foreign interests both in American locations and abroad.

Beginning an MRI Project

MRI brings creativity and scientific discipline to the design and performance of research programs. An MRI project begins with discussions between the client and Institute staff to determine precise objectives. A written proposal then outlines the scope of research, methodology, staff involved, and statements of time and cost. Upon acceptance, a contract defines necessary details. MRI client representatives meet regularly to review research progress; project reports are furnished as required by the client. Research results are treated as confidential information, and all findings including appropriate patent rights become the client's property.

ECONOMIC IMPACT AND TECHNOLOGICAL PROGRESS OF NASA RESEARCH AND DEVELOPMENT EXPENDITURES

Volume I

EXECUTIVE REPORT

September 20, 1988

For

The National Academy of Public Administration
Washington, D.C.

MIDWEST RESEARCH INSTITUTE 425 Volker Boulevard Kansas City, Missouri

PREFACE

This is the first of three volumes that present the findings of a research inquiry into the economic impact and technological progress associated with NASA's research and development expenditures. The titles of the three volumes are:

- Volume I: Executive Report, Economic Impact and Technological Progress Related to NASA's R&D Expenditures
- Volume II: Economic Impact of NASA R&D Expenditures
- Volume III: Case Studies of Technological Progress: Digital Communications, Civil Aeronautics Performance and Efficiency, Future Technology Areas

The research was sponsored by the National Aeronautics and Space Administration through a subcontract to Midwest Research Institute from the National Academy of Public Administration.

Midwest Research Institute's management team for the project included John McKelvey, President and Chief Executive Officer, who served as project director. Linda W. Thornton, Director of MRI's Economics and Management Sciences Department, served as project manager. Bruce W. Macy, Director of MRI's International Programs, served as administrative manager. Principal research economists on the project included Michael Maasen, K. W. Lum, Peter Soule, and Robert E. Gustafson. Principal research technologists included Jack R. Wimer, who also served as task manager, and Howard M. Gadberry. Cherie Wyatt, Daniel R. Keyes, Gerald Taylor, and James Becker assisted in the research.

For the economic analysis, principal consultants were Dr. Zvi Griliches of Harvard University; Dr. John Kendrick of George Washington University; and Dr. Dennis Starleaf of Iowa State University. For the case studies, principal consultants were Dr. Irving S. Reed, Professor of Computer Engineering at the University of Southern California; and Dr. Robert Peile of Cyclotomics, Inc., Berkeley, California, and Professor of Electrical Engineering at USC.

The project team benefited from the suggestions of the NAPA Advisory Panel chaired by General W. Y. Smith, President, Institute for Defense Analysis, and composed of Dr. Ruth M. Davis, President, Pymatuning Group, Inc.; Mr. Michael Devine, Associate Vice President, Florida State University; Dr. John Kendrick, Department of Economics, George Washington University; Dr. Gary Robbins, President, Fiscal Associates; Dr. Eleanor Thomas, National Science Foundation, Division of Policy, Research, and Analysis; and Mr. Edward Wenk Jr., Professor of Engineering and Public Affairs, University of Washington.

Special thanks are due to Ed Kilgore, the NAPA Project Officer; and to Frank Coy at NASA and Ron Philips, consultant to NASA.

Midwest Research Institute also appreciates the contributions of over 200 scientists and engineers interviewed at NASA headquarters and R&D centers during the course of the study. The research team would like to extend our appreciation to several NASA employees who served as designated liaison persons at the various research centers. These persons provided a wealth of history, background, and cultural knowledge about the programs studied, as well as provided a central point of contact for scheduling, interview requests, follow-up information, and the massive amount of paper generated during this effort. Although many inside NASA participated, our special thanks to Nancy Guire and Jyles Machen at the Marshall Space Flight Center in Huntsville, Alabama; Dr. Terry Cole and Marshal Alper at the Jet Propulsion Laboratory in Pasadena, California; Mr. Jack Murphy at the Ames Research Center at Moffett Field, California; Neal Saunders, Joe Saggio, and Pat Parker at the Lewis Research Center in Cleveland, Ohio; A. Gary Price at the Langley Research Center; Henry Plotkin and Steve Holt at the Goddard Space Flight Center in Greenbelt, Maryland; Nancy Lovato at the Ames-Dryden Flight Test Center at Edwards Air Force Base, California; Joe Loftus at the Manned Spacecraft Center in Houston, Texas; and Tom Hammon at the Kennedy Space Flight Center at Cape Canaveral, Florida. Additional guidance and encouragement were provided by Paul Ceruzzi, Associate Curator of the National Air and Space Museum.

Also deserving of appreciation are those private sector communications experts who gave of their time so that this report could be made as accurate as possible. Deserving of special thanks for reviewing this report are Dr. Elwyn Berlekamp of Cyclotomics, Inc.; Dr. Gustave Solomon of Hughes Aircraft; Dr. Andrew J. Viterbi of Qualcomm, Inc.; Mr. Neil Glover of DST, Inc.; and Dr. Solomon Golomb of the University of Southern California. Their insights and historical perspectives on early drafts were crucial to this project.

For the aeronautics report, Mr. Richard Hines and Mr. Bill Webb of Pratt & Whitney; William Clapper and A. F. Schexnayder of General Electric; Cal Watson, Don Hayward, and Dr. Bannister Farquttar of Boeing; and Max Klotzsche of McDonnell Douglas deserve many thanks for sharing with us their knowledge and insights.

The findings and judgments expressed in the report are those of the MRI project team and do not necessarily reflect the views of the National Academy of Public Administration or the National Aeronautics and Space Administration, nor those of any companies or individuals surveyed.

Sincerely,

MIDWEST RESEARCH INSTITUTE

John McKelvey
President and
Chief Executive Officer

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

> "Thirty years ago, there was no satellite communications industry. Today that industry generates gross annual revenues from sales of services and equipment exceeding $6 billion, provides an indispensable service to people, businesses, and governments throughout the world--and is responsible for returning more <u>each year</u> in tax revenues than the entire 30-year NASA investment cost the U.S. taxpayers.
>
> "Perhaps even more significant, although not as obvious, is NASA's role in driving technologies which benefit the U.S. economy and the nation's security across the board. Requirements posed by NASA programs like Apollo, planetary exploration, and the Shuttle have produced miniaturized electronics, power systems and components, automatic checkout equipment, computers and software, high-volume data processing and communications, guidance and control systems, high-strength materials--the list is virtually endless. These technologies have transformed American business, spawned hundreds of new products and services, and made innumerable contributions to national defense."[1]

In 1971 the National Aeronautics and Space Administration commissioned Midwest Research Institute (MRI) to conduct a macroeconomic analysis to measure the extent of the benefits of NASA R&D expenditures on growth in the U.S. economy. This research was augmented with two case studies, synchronous communication satellites and space crew support systems. The case studies detailed the substantive contributions and benefits of these NASA-related technologies to NASA programs, the private sector, and the American public in general. The study was well received and was used extensively by NASA in the 1970s to depict its role in U.S. economic growth and technology transfer.

In the fall of 1987, NASA commissioned the National Academy of Public Administration (NAPA), with MRI as a subcontractor, to conduct further research and to evaluate NASA contributions in the 1948-1986 time frame. The objectives of this latest study are to:

- Measure the impact of technological change on the economic growth of the nation, and characterize NASA's contribution to the growth process.
- Identify linkages between the technology generated by selected NASA missions and the broader economic benefits.
- Identify and characterize future benefits of selected NASA programs.

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[1] "The Civil Space Program: An Investment in America," Report, American Institute of Aeronautics and Astronautics Workshop, Airlie House, Virginia, November 17-18, 1987.

- Identify and characterize the economic impact of continued investment in NASA R&D programs.

This Executive Report presents MRI's findings and conclusions.

A primary objective of the earlier study by MRI was to measure the impact of R&D expenditures on the national economy. While R&D expenditures do have a nearly immediate economic impact through employment and payroll, the primary economic effects of R&D are felt over time. The 1971 study findings indicated that the average dollar spent on R&D returns about $7 in technology-induced economic gain over an 18-year period following the expenditure.

The approach MRI took in the 1971 study was based on methodologies developed by Dr. Robert Solow.[2] Dr. Solow was honored in 1987 with a Nobel Prize for Economics for his pioneering work in measuring total factor productivity. The approach MRI used, though relatively new at the time, has stood up under critical review in the 17-year period following the release of the report.

MRI's current study has been designed to be similar in approach and content to the 1971 study. The 1988 study primarily uses Dr. Robert Solow's approach in measuring the impact of technology on economic growth, but it incorporates refinements developed by other economists in recent years.[3] The 1971 study estimated economic impact during the period of 1948 to 1968; the 1988 study covers not only the original period but extends the estimates through 1986. The findings of the 1988 study, which incorporate essentially the same qualifying assumptions as in 1971, are:

- R&D expenditures have been an excellent national investment.

- On the average, each dollar spent on R&D returns about $9 in technology-induced economic gain over an 18-year period following the expenditure.

- The discounted rate of return ranges from 19 to 35 percent annually (depending on the assumptions made regarding the time-lag relationships between an R&D expenditure and its contribution to productivity growth).

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[2] Robert M. Solow, "Technical Change and the Aggregate Production Function," *The Review of Economics and Statistics*, August 1957.

[3] Edward F. Denison, *Why Growth Rates Differ: Postwar Experience in Nine Western Countries* (Washington, D.C.: Brookings Institution, 1967); *Accounting for U.S. Economic Growth, 1929–1969* (Washington, D.C.: Brookings Institution, 1974); *Accounting for Slower Economic Growth: The United States in the 1970s* (Washington, D.C.: Brookings Institution, 1979); and *Trends in American Economic Growth, 1929–1982* (Washington, D.C.: Brookings Institution, 1985).

Also, reviews and comments by Drs. Z. Griliches, J. Kendrick, E. Denison, and N. Terleckyj.

- The $148 billion, in 1982 dollars, spent on NASA R&D during the 1960 to 1986 period has returned to the U.S. economy at least $950 billion through 1986 and will continue to produce payoff through 2004, at which time the total payoff will be an estimated $1,338 billion.

MRI used the payback coefficient of $9 to $1 to measure the economic impact of NASA R&D. The $9 to $1 payback is slightly higher than the estimate of $7 found in the earlier study. Differences in these results are attributable, for the most part, to methodological refinements developed in the 1971 to 1988 time period.

Any economic estimation requires an approach based on certain underlying assumptions. Critics of the production function approach as it is applied to NASA R&D in this study may have concerns that (1) the gains ascribed to the stock of technical knowledge measured by R&D expenditures are overstated and (2) there is no empirical evidence for the assumption that NASA R&D is representative of the average of all R&D.

To address the first issue, MRI conducted a sensitivity analysis which showed that a 10 to 30 percent overestimation of the economic gains attributable to R&D would reduce the R&D payback from $9 to a range of $8.50 to $6.50. If, in fact, the MRI payback figure is overestimated even by the worst case of 30 percent and the coefficient is more in the range of 6.5 to 1, the $148 billion spent on NASA R&D during the 1960 to 1986 period would return an estimated $966 billion rather than the $1,338 billion estimated return from a 9-to-1 payback. In either case, the payback from NASA R&D would be substantial.

The second principal assumption in the MRI study is that NASA R&D expenditures have the same economic payoff as the average of all R&D. In other words, NASA R&D is assumed to contribute as much to productivity growth as the average of all R&D. To illustrate and support this assumption, MRI selected two case studies to trace how technology developed by specific NASA missions has been applied commercially:

- Digital communications--including the use of error-correcting codes and data compression in processing digital signals for modern-day digital communication and data storage.

- Civil aeronautics performance and efficiency--centering on a series of advances in aerodynamic drag reduction, advances in propulsion, and advances in flight control technology.

MRI chose these two from a list of over 250 major NASA technologies. Our results from these two case studies, as well as the knowledge we have gained in reviewing the 250 principal NASA technologies, indicate a very high payback from the NASA R&D investment. In narrowing the possibilities to two, MRI visited all of the major NASA R&D centers and reviewed NASA's research and technology operating plans (RTOPS), NASA's Tech Briefs and *Spinoffs*, and key NASA patents. During the course of the project, MRI staff interviewed over 200 NASA personnel familiar with past and current technological achievements.

The MRI study team chose the case studies to be representative of the breadth and diversity of NASA programs. The team sought to include both sides of NASA--aeronautics and space--and to select two vastly different technologies--incremental vs. leapfrogging advances--yet with common characteristics from the point of view of their beneficial offspring.

It is clear that without NASA's mission objective of communicating in deep space, digital communications would not be as advanced as it is today. "NASA pushed this technology further than any other entity."[4] The work of the MRI research team documents that NASA's support and extensive R&D funding made possible many comprehensive and ground-breaking advancements in coding theory. For many years coding was considered to be an esoteric and impractical approach to communications, yet it provided NASA an excellent alternative to adding weight, power, and complexity to spacecraft. The case study of digital communication/ error-correcting codes illustrates how a technology advanced by NASA to meet the mission requirements for deep space communications has spawned a family of high performance and productivity-enhancing electronic devices with annual sales expected to reach over $17 billion by 1990.

Likewise, NASA's role in civil aeronautics is a good example of why the United States has a decided edge in the world's commercial aircraft market. Improvements in civil aeronautics performance and efficiency have spanned some 70 years since the early days of the National Advisory Committee on Aeronautics (NACA). This report summarizes a series of advances aimed at enhancing the performance and efficiency of civil aircraft. The cases cited are intended to illustrate the complex paths by which new knowledge applicable to the design, construction, and operation of modern aircraft comes into being; the interactions between the aerospace industry and government centers of research and technology; the numerous evolutionary changes and improvements that are contributed from many sources; and the often prolonged period of time required to validate, demonstrate, and refine technological advances before they become accepted commercially and widely used.

As a result of NASA's continuing R&D in aeronautics, man can fly farther, faster, higher, and more efficiently and safely than thought possible 20 years ago.

This Executive Report summarizes the economic impact of NASA's research. Part I explains the methodology, findings, and projections of economic benefits resulting from NASA R&D. Part II presents the technology advances and resulting benefits from digital communications, civil aeronautics performance and efficiency, and seven future technology areas.

[4] Interview with Irving Reed at his office at the University of Southern California, April 28, 1988.

PART I: ECONOMIC IMPACT OF NASA R&D

CHAPTER I. SCOPE OF WORK AND METHODOLOGY

A. SCOPE OF WORK

The scope of work encompassed nine research tasks:

- MRI researched current methodologies and data relating to multifactor productivity analysis. MRI adopted the most recent multifactor productivity indices developed by the Bureau of Labor Statistics to measure the productivity growth of the U.S. private business sector from 1948 to 1986.

- Using a multifactor productivity index implicit in the production function, MRI assessed quantitatively the gains in output due to (1) increases in labor and capital inputs and (2) improvements in multifactor productivity.

- Based on other economists work, MRI selected seven fundamental factors (including the stock of technical knowledge measured by R&D expenditures) that have significant influence on multifactor productivity.

- MRI developed measures for these factors and assessed their respective contributions to multifactor productivity growth over time.

- MRI measured empirically the quantitative relationships assumed to exist between R&D activities and productivity growth due to the stock of technical knowledge.

- MRI performed a sensitivity analysis to determine how other plausible assumptions affected the estimate on the rate of return for R&D.

- MRI compared its approach and results with other studies.

- Within the preceding analytical framework, MRI examined the economic impact associated with the technological stimulus provided by NASA R&D, assuming NASA R&D to be no less productive than the average of all R&D. (See Section C for arguments in support of this assumption.)

- Based on the model previously developed, MRI summarized possible economic benefits of continued investment in NASA R&D programs.

B. METHODOLOGY

The approach used by MRI utilized a macroeconomic production function model to estimate the aggregate effect of research and development (R&D) on productivity.

The strengths and weaknesses of the aggregate production function approach are well documented in the literature.[1] The primary criticism of this approach, however, is that many improvements in the quality of goods and services due to R&D activities are not adequately reflected in the existing aggregate economic series and cannot be accurately measured. One solution to these deficiencies is to conduct an intensive microeconomic analysis of a particular technology or group of technologies resulting from R&D expenditures. With this in mind, MRI has augmented and supported its economic analysis with case studies of two specific technologies that illustrate the ways and the velocity with which the results of NASA R&D filter through the U.S. economy.

1. Enhancements in the Methodology

Compared with the 1971 study, MRI's 1988 study has incorporated significant improvements in the following areas.

- Broader economic sector and longer time period: The current study was performed for the entire private business sector between 1948 and 1986, while the 1971 study was limited to the private nonfarm sector for the period of 1948 to 1968.

- More accurate and reliable data: MRI obtained more accurate and reliable data on the measurement of productivity growth and changes in labor composition. These data were provided by the Bureau of Labor Statistics (BLS). Since the 1971 study, the BLS has undertaken an ambitious program to measure multifactor productivity changes and to account for changes in aggregate labor quality brought about by demographic shifts in the work force.

- Better measure of productivity growth attributable to R&D: MRI was able to account for more factors with significant influence on productivity growth. The current study measures the effect of six factors (not including R&D) on productivity growth, while the 1971 study was limited to two factors (changes in the gender mix and education level of the work force). MRI was able to measure the effect of these six factors on productivity growth based largely on the 30 years of work undertaken by Dr. Edward Denison.

- Two statistical approaches: The current study uses two statistical approaches to estimate the rate of return for R&D investments.

- Sensitivity analysis: The current study includes a sensitivity analysis that determines how other plausible assumptions affect MRI's estimates.

2. Reviews and Comparisons

Since Dr. Solow's work on aggregate production function in 1957, many economists have used his basic approach to measure the contributions of technology to economic growth. In this study MRI economists have incorporated the approach and refinements developed by the premier economists in this field. Recognizing that economics is not an exact science, MRI has sought the advice and counsel of many of these economists to gain a more thorough understanding

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[1] Zvi Griliches, "Issues in Assessing the Contribution of Research and Development to Productivity Growth," *The Bell Journal of Economics*, Vol. 10, No. 1, Spring 1979, pp. 92-116.

of the relationship between R&D and productivity growth. Principal reviewers included Dr. John Kendrick at George Washington University, Dr. Zvi Griliches at Harvard University, and Dr. Dennis Starleaf at Iowa State University. These three economists reviewed the work of MRI economists as the study progressed. MRI also discussed its methodological approach and sought current information on methodological refinements from Dr. Edward Denison and Dr. Nestor Terleckyj during the model development phase of the study. Further, the MRI report was reviewed at four junctures by the NAPA Advisory Panel.

In addition to the review process, MRI also compared its rates of return with those reported in other studies. (This analysis was also the basis for the bounds, 10, 20, and 30 percent, used in the sensitivity analysis.) In Table 1, MRI's estimates are compared with other studies.

As can be seen in the table, the rate of return determined by MRI (19 to 35 percent) falls in the middle range of estimates developed by other economists. This occurs even though the MRI study team ascribed a high residual to R&D (a remainder of 0.735 percentage points after accounting for the portion of multifactor productivity growth attributable to six fundamental factors).

Conversely, in Griliches' work,[2] he estimated that R&D investment contributed no more than 0.3 percentage points to the rate of growth measured in multifactor productivity. Denison[3] claimed that organized R&D expenditures contributed an estimated 0.2 percentage points or at most 0.3 points to the productivity growth rates. Sveikauskas[4] suggested that the direct contribution of R&D to productivity growth was between 0.1 and 0.2 percent annually in the nonfarm business sector.

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[2] Zvi Griliches, "Research Expenditures and Growth Accounting," in B. R. Williams, ed., *Science and Technology in Economic Growth*, 1973, pp. 59-95.

[3] Edward F. Denison, *Accounting for Slower Economic Growth: The United States in the 1970s*, Brookings Institution, 1979; and *Trends in American Economic Growth, 1929-1982*, Brookings Institution, 1985.

[4] Leo Sveikauskas, "The Contribution of R&D to Productivity Growth," *Monthly Labor Review*, U.S. Department of Labor, Bureau of Labor Statistics, March 1986.

TABLE 1

A COMPARISON OF STUDIES OF RATE OF RETURN FOR R&D

Author	Date	Scope of Research	Estimated Rate of Return/Contribution to Economic Growth, %	Empirical Methodology
Shultz	1953	Agriculture	35-170	Computational analysis
Griliches	1958	Hybrid corn	35-40	Cost/benefit
Peterson	1967	Poultry	20-30	Cost/benefit
Eastman	1967	Military	9-40	Cost/benefit
		Aircraft	82	
Weisbrod	1971	Poliomyelitis	11-12	Cost/benefit
Ardito & Barletta	1971	Corn, wheat, etc.	54-82	Cost/benefit
Ayeh & Schuh	1972	Cotton seed	70	Consumers surplus
Akimo & Hayami	1975	Rice	33-75	Consumers and producers surplus
Griliches	1964	Agricultural	53	Regression
Mansfield	1965	Manufacturing industries	2-999	Computation and regression
		Chemical and petroleum	30, 40-60	
Evenson	1968	Agriculture	57	Regression
Minasian	1969	Chemical	50	Regression
Peterson	1971	Poultry	50	Regression
MRI	1971	Macroeconomic (private nonfarm business sector)	33	Computation and regression
Griliches	1973	Manufacturing industries	20	Regression
Terleckyj	1974	Manufacturing industries	30	Regression
Griliches	1980	Manufacturing firms	17	Regression
MRI	1988	Macroeconomic (private business sector)	19-35	Computation and regression

Sources: Paul Kochanowski and Henry Hertzfeld, "Often Overlooked Factors in Measuring the Rate of Return to Government R&D Expenditures," Policy Analysis, 1981, pp. 156-167.

Nestor E. Terleckyj, "Effects of R&D in the Productivity Growth of Industries: An Exploratory Study," National Planning Association, 1974.

Edwin Mansfield, "Microeconomics of Technological Innovation," as reprinted in Ralph Landau and Nathan Rosenberg, ed. The Positive Sum Strategy, Harnessing Technology for Economic Growth (National Academy Press, Washington, D.C., 1986), pp. 307-325.

Kendrick[5] estimated higher contributions to productivity growth from R&D expenditures: 0.85 percentage points in 1948-1966 and 0.71 points in 1966-1973. Kendrick's high estimates are attributable, for the most part, to a large productive R&D stock. He counted all R&D stock performed in the business sector including all that was devoted to new and improved products and all that was financed by federal government.

The MRI study estimated the rate of return to R&D by regressing the assumed economic gains attributable to the technical stock of knowledge (measured by R&D expenditures) (in constant dollars) on the changes in all R&D stock. Whereas Griliches, Denison, Sveikauskas, and Kendrick estimated the contribution of R&D investments to the productivity growth rates by multiplying the changes in productive R&D stock as a percentage of output (mostly privately financed R&D) with the assumed rate of return to R&D.

In summary, the MRI finding of a 9 to 1 payback rate is equivalent to the estimate of 0.3 percentage points contribution to productivity growth determined by Griliches. If the 9 to 1 payback rate is overestimated by 30 percent, the resulting payback would be 6.5 to 1, equivalent to the estimate of 0.2 percentage points determined by Griliches and Denison.

In spite of these differences, our analysis shows that MRI's estimated payback rate based on all R&D stock is equivalent to Griliches' and Denison's estimated R&D contribution to productivity growth rates which are based on privately financed R&D stock.

The findings of both MRI's 1971 and current studies lead to the conclusion that, on the average (including good, bad, and indifferent projects), R&D expenditures have been an excellent national investment.

3. Limitations of the Study

Many questions remain to be answered before there is a thorough understanding of the relationship between R&D and productivity growth and of the factors that influence both. The limitations of the current study are noted below.

First, there have been intensive discussions regarding the question of how well the multifactor productivity index measures productivity growth. These debates directly involve the measurement of output, input, and productivity change. Because of the inadequacies inherent in the National Income and Product Accounts, much of reported R&D is expended in areas where its direct contribution to output is not measured (such as improvements in quality of goods and services).

Second, MRI selected six fundamental, statistically observable factors other than technical knowledge to account for changes in multifactor productivity. The selection of these factors was based on Denison's work as modified and

[5] Also see John W. Kendrick, *The Formation and Stocks of Total Capital* (New York: National Bureau of Economic Research) 1976.

extended in consultation with other scholars. MRI has also investigated the impact of other productivity determinants such as foreign trade effect, energy effect, labor disputes, weather in farming, worker safety and health, and dishonesty and crime. The net contribution of these factors to productivity growth is less than 0.01 percent and has little effect on our estimates. After apportioning their share of productivity growth to each of these six factors, MRI attributed the balance to the stock of technical knowledge (measured by the R&D expenditures) and then conducted a sensitivity analysis to determine how changes in this assumption affected the results.

Third, problems arise in defining the stock of R&D. Little theoretical or factual knowledge exists on deciding the appropriate lag structure, and the available data base does not inspire much confidence in our ability to measure it empirically. As a result, MRI used various assumptions to construct an R&D capital stock. For example, MRI assumed that the time lag between R&D investments and their first contributions to output varied from three to eight years. It was further assumed that the Poisson distribution would describe the probability of the lifetime of contributions to output made by an R&D activity. The total time span (payout period) considered was 18 through 20 years.

Fourth, the estimated payback coefficient provides information only on the average returns to R&D investments in the past and whether they appear to be changing over time. However, it cannot be used to predict whether any particular proposed R&D project has a high likelihood of success.

Fifth, the current study assumes that all R&D is homogenous. We had attempted to estimate the rate of return for different types of R&D by using federally financed R&D, privately financed R&D, and other types of R&D as independent variables in the regression equations. However, because of multicollinearity problems, we were unable to obtain reliable estimates. The problem of multicollinearity arises from the fact that these data moved together very much over the period of observation, and it is difficult to determine their separate contribution with any precision. Further research and investigation would be needed to measure the rate of return for different types of R&D.

As a result, MRI assumed that NASA R&D is no less productive than the average of all other R&D. Although MRI has not tested this assumption empirically, the case studies of the two specific technologies and other scholars' studies provide evidence to support this assumption. Further research is needed to (1) investigate how innovations differ between NASA R&D and other R&D, and (2) measure the productivity of NASA R&D related to other R&D.

CHAPTER II. ESTIMATES OF ECONOMIC IMPACT

A. ECONOMIC IMPACT OF R&D IN GENERAL

The major findings and conclusions obtained from our investigation of the economic impact of technology in general on the U.S. economy during the 1948 to 1986 time period are:[1]

- Total output of the private business sector (gross product in constant 1982 dollars) increased from $870 billion in 1948 to $2,925 billion in 1986.

- Cumulatively, total output for the period was approximately $67.7 trillion. If there had been no growth in multifactor productivity since 1948, the stock of labor and capital applied would have yielded a cumulative output of only $45.9 trillion. Improvements in multifactor productivity (resulting from those factors other than labor and capital that influence productivity growth) contributed $21.8 trillion (or about 32 percent) of the total cumulative output from 1948 to 1986.

- About 36 percent of the cumulative gain in output due to improvements in multifactor productivity was attributed to six fundamental, statistically observable factors. The balance of 64 percent was ascribed to the stock of technical knowledge measured by current and past R&D expenditures.

- On the average, each dollar spent on R&D returns about $9 in technologically induced economic gain over an 18-year period following the expenditure. The discounted rate of return ranges from 19 to 35 percent annually, depending on the assumptions made regarding the time lag relationships between R&D expenditure and its contribution to productivity growth. The relationship between R&D expenditures and gains in output attributable to R&D was explored econometrically. Two statistical methods were used to estimate the rate of return of R&D investments.

- Changes in the lag between R&D occurrence and its effect on productivity have little effect on the R&D payback estimates. Differing lag times will, however, affect discounted rates of return. If the Griliches deflator (instead of the GNP deflator) is used to convert the R&D expenditures into real terms, the original results are not greatly changed. Statistical evidence indicates that the R&D payback coefficient fluctuated during the period of 1974 and 1986. Finally, as a worst-case scenario, if one assumed a 30 percent reduction in the gains in output attributable to R&D, the R&D payback coefficient would reduce from 9 to 1 to about 6.5 to 1. A sensitivity analysis was conducted to make these determinations.

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[1] The analytical methodologies, research procedures, assumptions, and the underlying rationales for each are presented in detail in the fuller technical report entitled "Part II--Economic Impact of NASA R&D Expenditures."

B. ECONOMIC IMPACT OF NASA R&D

Based on the assumption that NASA R&D expenditures had the same payoff as the average R&D, MRI used its estimated payback coefficient (9 to 1) to measure the economic impact of NASA R&D.

- The $148 billion, in 1982 dollars, spent on NASA R&D during the 1960 to 1986 period had returned at least $950 billion through 1986 and will continue to produce payoff through 2004, at which time the total payoff will be $1,338 billion. The discounted rate of return ranges from 19 to 35 percent per annum depending on the lag distributions. Differences in lag times affect the flow of R&D-induced gains in output and consequently change the discounted rate of return. However, the total cumulative impact will remain unchanged because change in the lag structures has little effect on the R&D payback estimates.

- To address the concern that federal R&D expenditures and by inference NASA R&D expenditures, stays primarily in the government sector (and is thus less productive), MRI conducted an analysis on NASA R&D spending, based on NASA's annual procurement report. It is estimated that at least 80 percent of these expenditures are related to research and development activities. Based on this report, over 70 percent of NASA direct awards to principal contractors were given to business firms in three broad industrial categories (Standard Industrial Classification Codes 36, 37, and 73). The U.S. input-output model was used to illustrate how these expenditures are further filtered into the economy. It also sheds light on both the direct and indirect impacts of NASA spending on industries and other sectors of the economy. Examples:

  SIC 361-362, Electrical Industrial Equipment Industry: 59 percent of the output (sales) of the electrical industrial equipment industry was used (purchased) by 45 (of 85) other manufacturing industries. Of the remaining 41 percent, gross private investment accounted for 30 percent and federal and state government purchases accounted for only 6 percent.

  SIC 365-366, Communication Equipment Industry: 21 percent of the output of the communication equipment industry was used by 35 industries. The remaining 79 percent was sold to final users as personal consumption, private investment, federal and state government purchases (25 percent), and other final users.

  SIC 372, Aircraft and Parts Industry: 21 percent of the output of the aircraft and parts industry was sold to industrial users, 41 percent was purchased by the federal government, 25 percent was exported out of the United States, and 12 percent was used for investment.

  SIC 73, Business Services Industry: About 83 percent of the output of the business services industry was sold to at least 70 industries as input.

C. PRODUCTIVITY OF NASA R&D VS. OTHER R&D

A principal, underlying assumption of MRI's approach is that NASA R&D is representative of, or at least no less productive than, the average of all R&D. MRI believes that this is a valid assumption.

However, there is concern among policymakers that more federal involvement in research and development may distort economic decisions and result in commercial failures, and that more federal support may waste taxpayers' money. Many studies have been undertaken to resolve this legitimate concern. According to Martin Neil Baily and Alok K. Chakrabarti (economists at the Brookings Institution),[2] a large degree of low productivity growth in the United States has resulted from slow innovations, missed technological opportunities, and poorly invested capital. The private sector tends to underinvest in R&D because of the problems of appropriability and of risk. They conclude that additional federal support for both the basic and the applied R&D will be required to increase productivity growth in the United States.

The effects or rates of return of federally financed R&D on the productivity growth of the economy vary among government programs. Government-funded R&D programs for agriculture, health, and space undoubtedly have more spillover effect on productivity growth than purely military projects. As a result, without accounting for its heterogeneity, the contribution of all federally financed R&D is difficult to determine. Recent studies found weak and inconsistent correlations between all government-funded R&D and productivity in manufacturing industries.[3] These findings are inconclusive and should not be used to generalize the contribution of every government-funded R&D program. Recognizing such problems, economists attempted to estimate empirically the contribution of federally financed R&D productivity of the economy through its contribution to the productivity of privately financed R&D. Research studies (using a variety of different methodologies and different time periods) indicate that, in most cases, federally financed R&D expenditures stimulate privately financed R&D expenditures.[4]

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[2] Martin Neil Baily and Alok K. Chakrabarti, *Innovation and Productivity Crisis*, The Brookings Institution, Washington, D.C., 1988.

[3] Zvi Griliches, "Issues in Assessing the Contribution of Research and Development to Productivity Growth," *The Bell Journal of Economics*, Spring 1979, pp. 92-116.

E. Nestor Terleckyj, "Measuring Economic Effects of Federal R&D Expenditures: Recent History With Special Emphasis on Federal R&D Performed in Industry," paper presented to the National Academy of Sciences Workshop on the "Federal Role in Research and Development," November 21-22, 1985.

[4] Terleckyj, Ibid.

Many studies have been conducted to quantify the economic impact of NASA R&D. None of these studies have found that NASA R&D is unproductive, and there is no empirical evidence that specifically shows NASA R&D is less effective than other R&D. On the contrary, all these studies report very positive impacts of NASA R&D on the productive capacity of the economy. Based on our case studies and other scholars' studies, NASA R&D programs have also provided substantial benefits to the economy. Some of these economic benefits are general advances in science and technology; stimulation of private R&D spending; increased technology transfer; development of new products, new processes, and new industries. These five areas are discussed more fully in the next section on future benefits.

There is considerable evidence in MRI's two case studies to support the assumption that NASA R&D is as productive as other R&D. However, in order to accurately measure these benefits, much more research remains to be done on (1) how innovations differ between NASA R&D and other R&D and (2) comparing the productivity of NASA R&D with that of other R&D.

D. FUTURE ECONOMIC BENEFITS

This section provides a summary indication of possible economic benefit outcomes of continued investment in NASA R&D programs, focusing on the long-term technology enhancement and productivity impacts.

Using its model, MRI can project a stream of future economic benefits (in dollars) from an estimated R&D expenditure. MRI has developed various scenarios to estimate the economic impact of an increase in NASA R&D expenditures (in 1982 dollars). The cumulative impact of each scenario is summarized in Table 2.

TABLE 2

PATTERN OF GAIN IN ECONOMIC OUTPUT ATTRIBUTABLE TO CONTINUED INVESTMENT IN NASA R&D[a]

Scenario	(1) Continued Investments[b] in R&D From 1987 Through 1990	(2) Cumulative G(R&D)[c] $9 to 1	$6.5 to $1[e]	(3) Increase in Cumulative G(R&D)[d] $9 to $1	$6.5 to $1[e]
(3)	10% annual increase	1,440	1,040	102	74
(2)	5% annual increase	1,429	1,032	91	66
(1)	Remain constant at 1986 level	1,419	1,024	81	58

a Initial lag = 5 years, mean of G(R&D); lifetime distribution = 5 years; payout period = 18 years.

b The increase is based on the $2.291 billion NASA R&D expenditure in 1986.

c Cumulative G(R&D) = cumulative gains in output attributable to NASA R&D effort from 1960 through 2004 (in 1982 billion dollars).

d Increase in cumulative G(R&D) resulting from continued investment in R&D from 1987 through 1990 (in 1982 billion dollars).

e Worst-case scenario.

As discussed in the previous chapter, the $148 billion (1982 dollars) spent on NASA R&D during the 1960 through 1986 period will return $1,338 billion through 2004 at the 9 to 1 payback rate, or $966 billion at the worst-case 6.5 to 1 payback rate.

Scenario (3) shows that, using the 9 to 1 payback rate, a 10 percent annual increase in NASA R&D expenditures from 1987 through 1990 will produce a total payoff of $1,440 billion through 2004, a $102 billion increase over the $1,338 billion. Similarly, using the worst-case 6.5 to 1 payback rate, the 10 percent annual increase in NASA R&D expenditures will return $1,040 billion through 2004, a $74 billion increase over the $966 billion.

Column 3 indicates that a 10 percent annual increase in NASA's budget from 1987 through 1990 will increase the total payoff by $102 billion at a $9 to $1 rate or $74 billion at the worst-case $6.5 to $1 rate through 2004.

These projections are based on the assumptions made for the lag structures. As previously mentioned, differences in lag structures will not change the ultimate total effect of the R&D-induced gains in outputs because changes in lag structures have little effect on the R&D payback estimates.

Investments in R&D are expensive and risky, especially in the case of projects attempting significant technological breakthroughs such as space explorations. But, as has been discussed, recent studies conclude that federally financed R&D is important and is required to increase productivity growth. In the long run, R&D translates into economic gain.

In examining the process by which NASA R&D contribute to productivity, it is possible to classify these potential benefits in five main categories.

1. General Advances in Science and Technology

NASA's activities provide public goods that have important long-term effects on the productive capacity of the nation. Space exploration programs and other NASA R&D activities will continue to broaden the technological base of the United States on which future growth is predicated. Such contributions cannot be fully captured by private investors in the form of profit. Consequently, private investors often lack incentive to produce such goods, and they remain unproduced unless the government intervenes.

2. Stimulated Private R&D Spending

Research studies in the last several years indicate that, in most cases, private R&D expenditures have been positively related to government R&D expenditures. After the Department of Defense, NASA is the most significant federal R&D agent. Over the last decade, NASA has begun its commercialization process by encouraging and stimulating other industries to use NASA facilities and infrastructure to develop R&D projects. Undoubtedly, NASA will continue to play an important role in funding and stimulating private research and development.

3. Diffusion of New Knowledge and Refinement of Existing Technology

According to Baily and Chakrabarti,[6] a fundamental weakness affecting much of American industry is the failure to incorporate new technology effectively into production. Technological opportunities for growth were missed because industry executives chose not to employ available technology and the technical community was reluctant to make their innovations widely known.

NASA has actively supported R&D programs that aim at developing commercial innovations. NASA has also used different programs (such as technology utilization, patent licensing, and patent waiver programs) to transfer technology to the private sector or to encourage its transfer. There are other programs designed to disseminate information about new technology to business and general economy. In addition, NASA may also indirectly improve private sector research by enlarging the critical mass of technological personnel. As a result, continued investment in NASA R&D programs will help to increase capabilities to diffuse new knowledge and refine existing technology knowledge.

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[6] Baily and Chakrabarti, loc. cit.

4. New Products/Improved Process[7]

In addition to the new products and improved processes resulting from NASA R&D programs, the current space activities may well create an infrastructure that will lead to other space projects and improvements in our economic system not even thought of today. This is similar to a new type of infrastructure created by railroads and interstate highways: they not only made transport of materials and products cheaper and faster, but they also changed the shape of our cities and our way of living. There were economic effects hardly dreamed of at the onset of railroad and highway development.

5. New Industries

NASA R&D programs will continue to encourage the creation of new industries. The case study technologies investigated by MRI during this study clearly show that NASA R&D creates new industries. In addition, there is a whole frontier of potential new industries that can use the space environment. Space has great potential for economic growth and benefits. Some of the future commercial activities of space infrastructure are as follows.[8]

Transportation and launch services. This consists of transporting payloads into space for telecommunication, meteorological observations, and space experimentation. Transportation is considered as the most capital-intensive and mature component of space commercialization.

Communications satellites. The communications industry is one of the industries that underwent a technology-stimulated radical change. This began with the development of NASA's capability to launch satellites into orbit and retrieve data from them in the late 1950s and 1960s. The growth rate of the communications industry has been rapidly increasing. There will be even more rapid, exponential growth of the use of these satellites in commercial profit-making ventures. The total impact of the ability to transmit information easily and cheaply has yet to be determined.

Manufacturing and materials processing. Because of the absence of vibration, the near-perfect vacuum, the sterile environment, unfiltered sunlight, and microgravity, the space environment provides a potentially valuable laboratory for manufacturing certain chemicals, pharmaceuticals, and alloys. These

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[7] Henry Hertzfeld, "The Impact of NASA Research and Development Expenditures on Technological Innovation and the Economy," Proceedings of the International Colloquium on Economic Effects of Space and Other Advanced Technologies, Strasbourg, April 28-30, 1980, pp. 81-93.

[8] The following discussion is based on Jonathan Goodrich, Gary H. Kitmacher, and Sharad R. Amety, "Business in Space: The New Frontier?" *Business Horizons*, Indiana University Graduate School of Business, Vol. 30, No. 1, January-February 1987, pp. 75-84.

products can be produced more efficiently and in higher quality in space than on earth. Scientists envision the manufacture of these products on space stations and on free-flying platforms with compartments leased by industry.

Space stations and space platforms. The component modules of space stations and space platforms are potential products for space commercialization.

Defense. Defense weaponry and surveillance systems in space represent an important component of space commercialization.

Ground-based support. This includes the preparation and processing of payloads for flight, the manufacturing of the space shuttle, space suits, other space necessities, and providers of space insurance.

PART II: TECHNOLOGY CASE STUDIES

CHAPTER I. SCOPE OF WORK AND METHODOLOGY

A. INTRODUCTION

To illustrate the technology transfer process and to support the economic impact estimates, the MRI team selected two case studies and traced how technology developed by specific NASA missions is applied commercially and thus creates economic impact. The case studies selected are:

- Digital communications--including the use of error-correcting codes and data compression in processing digital signals for modern-day digital communication and data storage.

- Civil aeronautics performance and efficiency--centering on a series of advances in aerodynamic drag reduction, advances in propulsion, and advances in flight control technology.

Prior to selecting these two technology groups, the MRI team interviewed over 200 top managers, scientists, and engineers at NASA headquarters and at each of the nine major NASA research centers. In this process over 250 technologies currently being pursued by NASA were reviewed for potential economic impact. MRI was seeking technologies that clearly represent the way that NASA develops and transfers new knowledge based on research and development for specific missions.

Further, it was preferred that each of the technologies be distinct from each other. For example, the team wanted to examine a technology based on NASA's aeronautics work as well as NASA's space missions. The team wanted to examine technologies that would appear to have both concrete commercial applicability and counterintuitive applicability, such as deep space probes. The team also considered it instructive to examine a technology in the perfecting stage (aeronautics) as well as a technology that would be classified as pioneering (error-correcting codes).

These two technology case studies document key NASA technological advances and their effect on economic and technological progress in the United States.

B. METHODOLOGY

The objective of the case studies is to illustrate the processes whereby new technology is developed and commercially applied, with emphasis on the multiple ways in which NASA R&D has aided the accumulation and commercial application of new or improved scientific and technical knowledge.

The cases selected exhibit the major elements in the progression from scientific knowledge through technology to viable economic applications. Areas were chosen to permit exploring the aggregate effects of technological progress in a broad field rather than impacts stemming from individual inventions or innovations.

The complexity of the interactions between technology and the economy virtually defies any organized, comprehensive, or quantitative treatment. Technological progress is composed of a few major and countless incremental advances which are constantly being combined and recombined to satisfy public and private demand. Thus any application of technology represents the gathering of many technological threads to meet the objectives at hand. Ultimately, many of the individual threads also find applications beyond those of the original objective. A principal purpose of the case studies is to illustrate that both of these characteristics may be observed, and to show how they occur.

Before the case studies could be chosen, certain questions concerning the nature, range, and origins of NASA technology needed to be answered:

- What are representative technical fields in which NASA has made significant contributions?

- Which of these technical developments is judged likely to result in economic consequences?

Answering these questions involved a two-stage process--careful analysis of documents reporting NASA's developments, and personal interviews with NASA personnel familiar with technical achievements.

Initially, the MRI team reviewed NASA's research and technology operating plans (RTOPs) for 1985 through 1987, and secondly, NASA's Tech Briefs. These are concise descriptions of specific technical developments that have achieved a significant level of technical advance. Since the program began, well over 4,300 such technical achievements have been documented. A review of NASA patents was complicated by the large number of cases resulting in the issuance of patents. MRI's attention centered on those NASA patents for which requests for licensure had been pursued. This document review was augmented by discussions with the patent officers at most of the NASA field centers visited. Finally, the NASA publication *Spinoff* was reviewed. Since 1971 *Spinoff* has reported on NASA's significant developments and chronicled certain technical advances that have progressed to application outside the original aerospace objectives.

The most productive method for identifying NASA technology developments involved personal interviews with approximately 200 NASA personnel familiar with past and current technical achievements. These interviews were conducted with key managers at NASA headquarters in Washington and at all of the major NASA field centers:

- Langley Research Center in Hampton, Virginia
- Lewis Research Center in Cleveland, Ohio
- Goddard Space Flight Center in Greenbelt, Maryland
- The Jet Propulsion Laboratory in Pasadena, California
- Ames Research Center at Moffett Field, California
- The Marshall Space Flight Center in Huntsville, Alabama
- The Ames-Dryden Flight Research Center at Edwards Air Force Base, California
- Johnson Manned Spacecraft Center in Houston, Texas
- The Kennedy Space Flight Center at Cape Canaveral, Florida

As these interviews were conducted, MRI attempted to query scientists, engineers, and section heads about those technical developments since 1970 they regarded as having been most successful or significant; and which technical developments had already received some degree of technical acceptance and use outside the space field, or were judged quite likely to have commercial significance in the near future.

The results of both the document review and personal interviews were combined to form a primary listing of NASA technologies expected to have commercial economic consequences.

The technologies were also screened for representativeness of NASA. The study team was concerned that any one technology case study might not be credible if it occurred in an area of obvious commercial interest--a sure winner, in other words. The team decided to choose technologies that represented both ends of the spectrum--technologies that would seem so far out that no commercial benefit might ever result and technologies that would appear to the casual observer as not having immediate commercial value.

Both these objectives were accomplished. The two technologies selected by Midwest Research Institute for case study were narrowed down in March 1988 to:

- NASA's contribution to digital communications, including the use of error-correcting codes and data compression.

- A series of NASA advances in aeronautics which have led and are leading to safer and more efficient commercial air transport aircraft.

In covering digital communications, MRI found that error-correcting code technology was once pronounced "dead" at a 1972 academic conference in Florida; yet 15 years later it is pivotal in electronic devices in our homes and offices. On the other hand, MRI cites an aeronautics technology, winglets, with obvious benefits from its beginnings--that 10 years later has only begun to see application.

CHAPTER II. DIGITAL COMMUNICATIONS

A. INTRODUCTION

In the area of digital communication, MRI's analysis centers on error-correcting codes and data compression, two technologies whose utilization has contributed to major advances in NASA's ability to communicate over vast distances in deep space. Because of its deep space needs, NASA played a major role in bringing coding and compression out of the theoretical era into an era of practical use and application.

Error-correcting codes (ECC) (also called error control coding or channel coding) have a rich history and today are broadly useful in hundreds of applications involving digital communications and data storage. Error-correcting codes are complex mathematical formulas that add context to numbers much as sentence structure adds context to words. The end result is that missing numbers, or data, can be regenerated based on the surrounding data that survive the transmission.

Noise is the natural enemy of digital communication. Error-correcting codes overcome noise. When proper error control coding is used, large amounts of signal-degrading noise can be tolerated in the communication channel--whether it is generated by millions of miles of space, or by a high data rate over normal phone lines, or by a simple fingerprint on a compact audio disk.

For 30 years, from the early days of tracking sounding rockets into the upper atmosphere to recent plans for digital voice and data communications with the space station, NASA has supported and nurtured this technology.

NASA contributed to the development of error-correcting codes by hiring, supporting, funding, and driving many of the giants in the channel coding field over decades of research. The chronology and the list of who's who in coding theory and practice are laced with NASA employees, former employees, consultants, and contractors, all seeking better codes and more efficient decoding schemes.

Error control coding, in turn, has played an important role in the development of NASA. This elegant, obscure technology is responsible for taking NASA deeper into space, returning larger quantities of data, with lower error rates than could have been achieved without substantial expenditures of money and years of work on brute force methods, such as more power, bigger antennas, and greater bandwidths.[1]

NASA helped improve the performance of these technologies, taking advantage of the improvements in computer chip circuitry. Today, these error-correcting codes, and to a lesser extent data compression, are extensively used in consumer products such as compact audio disks, optical computer memory storage, new-generation modems, facsimile machines, and high-end disk drive

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[1] G. D. Forney and E. R. Bower, "A High-Speed Sequential Decoder: Prototype Design and Test," IEEE Transactions, October 1971, p. 821.

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systems. But it was not until well into the '80s, over 30 years after their theoretical explanation, that coding was used in consumer electronics products. Even the most technology-oriented consumers had not heard of error-correcting codes until about 1982, when they appeared as part of the enabling circuitry behind the phenomenally successful compact disk audio system and on other optical storage media. NASA, however, had been heavily pursuing the theory and the utilization of error-correcting codes since 1959.

By using smaller and less expensive components while increasing the data transmission rates to phenomenal speeds, electronics firms today have created an environment of noise and error probability not unlike that of deep space communications. Thus, it is not surprising that technologies whose practical use was pioneered by NASA are now important parts of many commercial and consumer electronic and computer products. Additionally, an entire industry now exists composed of companies who design, fabricate, and sell error-correcting circuitry for a wide range of applications.

The mission payoff from NASA's long-term effort in the digital communications field has been clear. NASA has achieved a nearly one trillion-fold increase in communication capability (for a fixed distance, i.e., Earth to Saturn) since the early 1960s. Much of that increase is due to NASA-developed data coding and compression schemes. That magnitude of improvement outdistances even the fast-growing power of the computer over the same period.

B. RESEARCH AND DEVELOPMENT IN ERROR-CORRECTING CODES

For the past 40 years, nearly every paper written on the subject of error control coding has applauded the classic 1948 work of Claude Shannon.[2] Shannon opened the age of coding theory by postulating that a communications channel could be made more reliable by utilizing a fixed percentage of the channel for redundancy.

While the development of practical codes for error checking and error correction began concurrently with the publication of Shannon's theorems, a substantial period elapsed before codes of practical utility evolved. Early efforts were primarily directed toward parity checking, product codes, and the search for perfect packed codes. Irving S. Reed and Richard Hamming were among the first theorists to devote attention to devising a systematic decoding scheme. The Fire codes introduced in 1959 were the first codes designed to deal with bursts of errors. By 1960, when the BCH[3] codes and their subset, the Reed-Solomon codes, were disclosed, both mathematicians and communications engineers were still faced with three fundamental problems:[4]

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[2] Claude E. Shannon, "A Mathematic Theory of Communication," *The Bell System Technical Journal*, Vol. 27, July 1948, p. 418.

[3] Named for early codists Bose, Chaudhuri, and Hocquenghem.

[4] Elwyn Berlekamp, Key Papers in the Development of Coding Theory," IEEE Press, New York, 1974.

- How good are the best codes?
- How can we design good codes?
- How can we decode such codes?

These problems were essentially resolved during the 1960s, paced by the breakthroughs contributed by Peterson, Fano, Massey, Berlekamp, and Viterbi. The emphasis of work in this period tended to specialize around certain fields. Many information theorists worked on linear and cyclic block codes. The discovery and development of convolutional codes and the powerful strategy of concatenation occupied the efforts of another school of coding theorists. Systematic algorithms for efficient decoding provided a challenge primarily for engineers.

The design of circuitry to code and decode useful channel coding schemes was deferred until the mid-1960s because of the belief that decoding hardware would be prohibitively complex. Finally, the application of forward error-correcting schemes to real-world communications, data storage, and digital processing started to gain acceptance in the late 1960s.

Some of the key events in these five related areas of code development are shown in Table 3. The significant contributions of pivotal workers in each area are indicated at the time of each substantial contribution. The figure clearly illustrates the changing emphasis of coding development, from the basic theory of the 1950s to the more practical hardware and applications of the 1980s.

1. NASA's Role in Coding

The work of Shannon and his followers had been purely theoretical for 10 years when NASA was established in 1958. This theoretical bent would continue for almost another decade.[5] Yet NASA took an early interest in error control coding.[6] First, Solomon Golomb at the Jet Propulsion Laboratory (JPL), and later Warner Miller at Goddard Space Flight Center, and Dale Lumb at Ames Research Center were early advocates (early 1960s) of using channel coding in rocket telemetry and satellite communications. At JPL, Golomb, along with other communicating experts, created an entire working section on error control coding. It remains world class, even today. Before moving to Goddard, Miller used FM/FM transmissions and pulse code modulation in early sounding rocket research in the late 1950s. At Ames Research Center in 1966, Lumb recommended an experimental coding system as part of a satellite communications transmitter on a solar probe, Pioneer IX, launched on November 8, 1968. That successful experiment clearly demonstrated the utility of coding to the skeptics inside NASA.[7] Other NASA scientists and engineers working at JPL and other NASA centers were emboldened by the success of Pioneer IX.

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[5] Elwyn R. Berlekamp, Robert Peile, and Stephen H. Pope, "The Application of Error Control to Communications," *IEEE Communications Magazine*, Vol. 25, No. 4, April 1987, pp. 44-57.

[6] Interviews with I. S. Reed at the University of Southern California, and Warner Miller at Goddard Space Flight Center, January 20, 1988.

[7] Interview with Dale Lumb at Ames by phone, March 29, 1988.

TABLE 3

KEY EVENTS—DEVELOPMENT AND USE OF ERROR-CORRECTING CODES

	INFORMATION THEORY AND BLOCK CODES	CONVOLUTIONAL CODES CONCATENATED CODES	DECODING ALGORITHMS	DEVELOPMENT OF HARDWARE CODECs	APPLICATIONS
1948	Shannon *Information Theory*				
1950	Hamming *Parity Check (7,4)*; Golay *Perfect (23,12)*		Hamming *Decoding*		
1952				Rechtin *Phase Lock*	
1953				Golomb *Noise Sequences*	
1954	Reed-Muller *Codes*; Golay *Binary Coding*	Elias *Product Codes*	Reed *Threshold Decoding*	CODORAC *Correlation System*	Corporal *PN Guidance*
1955		Elias *Convolutional*		Welch *"M Sequences"*	
1956	Slepian *Array and Cosets*; Huffman *Huffman Codes*				
1958	Golomb-Welch *Comma-free Codes*			Green-San Soucie *High-Efficiency CODEC*	
1959	Fire *Burst Error Correcting*				
1960	Bose Chaudhuri *Hocquenhem Codes*; Reed-Solomon *Non-binary Codes*				
1961	Peterson *Systematic Decoding*; Mattson-Solomon *BCH Finite Fields*		Wozencraft-Reiffen *Sequential Decoding*		IBM 7030 *SEC Hamming Codes*
1962			Solomon *Group Weights*		
1963	Fano *Sequential Decoding*; MacWilliams *Weight Enumerator*	Fano *Sequential Decoding*	Massey *Threshold Decoding*		
1964	Solomon - Stiffler *Perfect Punctured Codes*		Berlekamp *Architecture*; Chien *Chien Search*		
1965		Wozencraft-Jacobs *Sequential Decoding*	Massey-Gallager *Stepwise Decoding*		
1966		Forney *Concatenated*	Solomon-McEliece *Weights of Cyclic Codes*	Meggitt *Early SEC Decoder*	Lumb *Pioneer 9 (1968 Launch)*
1967	Golomb *Lee Metric and Run-Length*	Viterbi *Viterbi Algorithm*	Jacobs-Berlekamp *Block Sequential Decoding*	Green *"Green Machine"*; Lin-Lyne *Pioneer Decoding*	

TABLE 3 (Concluded)

	INFORMATION THEORY AND BLOCK CODES	CONVOLUTIONAL CODES CONCATENATED CODES	DECODING ALGORITHMS	DEVELOPMENT OF HARDWARE CODECs	APPLICATIONS
1968	Posner *Combinational Structures*				Digital Cypress *Optical Storage*
1969					Pioneers 10-12; Mariner Mars
1970		Dorsch-Miller *Space Concatenated*; Forney *High-Speed Sequential*	Odenwalder *Hybrid Coding*		IBM 370 *(72,64) SEC-DED*
1971		Heller-Jacobs *Short-Constraint Viterbi*	Rice *Data Compression*	Linkabit *CODEC*; Layland-Lushbaugh *High-Rate Decoder*	IBM *Fire Codes*
1972	Welch-McEleice *Elias Bound Bettered*	Iwadare *Burst Conventional*			ERTS *Data Collection (1972 Launch)*
1974					
1975			Massey *Quick-Look-In*		
1976	Justesen *Approach Shannon Limit*	Lee *Byte Decoding*	Liu, Reed, Truong *Fast Fermat Transform*		Berlekamp *Tape Storage*
1977			Berlekamp *Soft Decision Decoding*		Goddard/CCSDS *Standard Coding (Adopted 1987)*; Voyager *Planetary Missions (1977 Launch)*
1978			Lim *Concurrent RS*; Acampora *Analog Viterbi*	Geist *160 Mbps for TDRS*	
1979		Solomon-Sweet *Connecting Block and Convolutional Codes*	Rice *Universal Noiseless Coding*		Sony/Phillips *RS for Compact Disk*
1980				Reed-Truong-Deutsch *Pipeline VLSI Chip*	IBM 3850 *Burst Correcting RS*
1981		Lin-Lee *Galileo Compression*			Intelsat V *120Mbsp Data*; Digital Equipment Corp. *Powerful RS Interleaved*
1982		Clark-McCallister *Convolutional for 30/20 Ghz*	Solomon-Sweet *Golay Code Decoding*	Maki *High-Speed TDRSS*; Berlekamp *Fast Bit-Serial*	
1984		Mackenthun *Block Convolutional*	Costello-Lin *Decode Extended RS*		
1985		Lin-Kasami *Cascaded and Hybrid*		Miller *High-Rate Processing*	DOD/NATO *JTIDS*
1986				Berlekamp *Hypersystolic RS Codes*	Voyager at Uranus *Compressed RS/Viterbi*; MCI *TDMA Network*
1987				Lahmeyer *RS for Galileo (Filed 1984)*; COMSAT *Convolutional CODEC*	

As the 1960s progressed, coding continued to be of interest mainly at JPL and Ames Research Center. Andrew J. Viterbi had assisted in the design of the telemetry equipment for Explorer I, the first successful U.S. satellite. Later he performed analysis on the use of orthogonal codes and biorthogonal codes for use in space communications (via Reed-Muller codes) on the Mariner series of spacecraft destined for Mars in the mid and late 1960s. Viterbi decoding is still an industry standard today, and Viterbi's approach is credited with making possible early large-scale application of forward error correction in communications.

However, the error-correcting codes which probably have had more economic impact than any other are the Reed-Solomon codes, a nonbinary family of block codes. Named for Irving S. Reed and Gustave Solomon, this family of codes took shape at MIT Lincoln Laboratories in 1959, about five years after the birth of the Reed-Muller codes. The Reed-Solomon codes, have far outshone their predecessors and peers in practicality, efficiency, and speed, resulting in broad application and usage.

Reed's strong background in modern algebra and his desire to become a "pure mathematician" led him to work on coding theory as a hobby in his spare time.[8] The chance happening that brought Reed and Solomon together occurred in early 1958. One of Reed's supervisors came to him with a dilemma: what to do with a young hire who was a mathematician, in fact, almost a pure algebraist. Reed readily agreed to take Solomon into his group and quickly showed him his work in coding theory. In 1959 they wrote a landmark four-page paper for the *Journal of the Society of Industrial and Applied Mathematics*.

Prior to publication, Solomon Golomb of JPL, by then a part of NASA, reviewed the work and offered a suggestion that Reed and Solomon incorporated into their paper published in 1960. Reed says today that Golomb influenced the development of the Reed-Solomon codes from that moment on.

For years after publication the Reed-Solomon code was viewed as interesting mathematics and little else. It simply did not appear to be practical with the computing capability of the day. Even in the mid '60s, when Golomb and others at JPL began to work on actually flying spacecraft with error-correction coding, they turned not to the elegant Reed-Solomon code but to the more straightforward but less capable Reed-Muller code. Such was the case for the next decade. Many people credit the emergence of the Reed-Solomon codes to decoding architecture developed by Dr. Elwyn R. Berlekamp, a coding theorist, engineer, and entrepreneur who at the time was a frequent contractor with JPL.

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[8] Interview with I. S. Reed at his office at the University of Southern California, April 28, 1988.

Since the Reed-Solomon code potential was unlocked in the mid-1970s, they have become popular for use on everything from inexpensive consumer electronic devices up to the planned 300 mpbs link with NASA's space station in the 1990s.

A powerful coding technique to achieve impressive coding results is to concatenate or cascade two more relatively simple codes. In this construction one code is known as the "outer" code and one as the "inner" code. Information to be transmitted is first encoded in blocks and then treated as an information stream encoded as a sequence of inner code blocks. At the receiver side, the demodulated data are first decoded for the inner code. Then the symbols released are decoded for the outer code.[9]

This coding technique was originally proposed by G. David Forney (in his 1966 book *Concatenated Codes*), who was working at the Codex Corporation under a NASA contract. Forney's idea was a good one, but no coding problem that was achievable with the computational capabilities of the day was complex enough in 1966 to require concatenation.

However, in the early 1970s, when NASA began to plan for the Voyager mission, the idea of concatenating two codes became attractive. A concatenated code of a given rate and block length is generally not as powerful as the very best single-stage code with the same rate and block length, but since decoding is implemented in stages, the complexity--and thus the weight, size, and power requirements--is reduced greatly.

NASA chose to concatenate the best of the two schools of thought in coding: nonbinary Reed-Solomon block codes for the outer codes and a Viterbi-decoded convolutional code for the inner codes. When NASA added the universal data compression techniques of JPL's Robert F. Rice, the most powerful code ever applied to an actual communication system was wrought. NASA thought enough of the code to patent it. This patent is often cited in the development of later devices which utilize Reed-Solomon error-correcting coding schemes.

2. Others Pursuing Error-Correcting Codes

A review of the literature indicates four major entities other than NASA with interest in coding theory for the first 20 years after the publication of Shannon's original paper. They are Bell Laboratories, IBM and its various suppliers, MIT Lincoln Labs, and the military.

In terms of work on coding theory, the military, IBM, and certainly Bell Labs had at least a 10-year head start on NASA, since NASA was not even established until 1958, and its predecessor, NACA, ventured only sparingly into fields outside pure aeronautics. Yet the value of error-correcting codes for satellite communications and recovery of planetary data was so great that NASA was forced to push code performance further than the other groups found

[9] Arnold M. Michelson, "Error Control Techniques for Digital Communications," p. 376, 1985.

necessary or economically feasible. The result was, a decade later, that NASA had demonstrated communications coding accomplishments that surpassed the results attained by the four other groups in performance and in elegance. These advances in channel coding and error correction can be traced to the nature and the difficulty of the space communications problem.

From a selected list of patents over the last 40 years,[10] it is clear that Bell Laboratories and IBM were premier in error-correcting code technology for decades. Recently Japanese firms have overtaken both Bell and IBM. (See Figure 1.) In fact, Bell Labs' dominance in those first 20 years (1948-1968) is comparable to the middle period domination of IBM (1968-1980) and the domination of Japanese firms during the past 10 years (1977-1987). Roughly 30 percent of key patents in this field during the past 10 years have been assigned to Japanese firms. In the past three years, this Japanese share has climbed to over 42 percent.

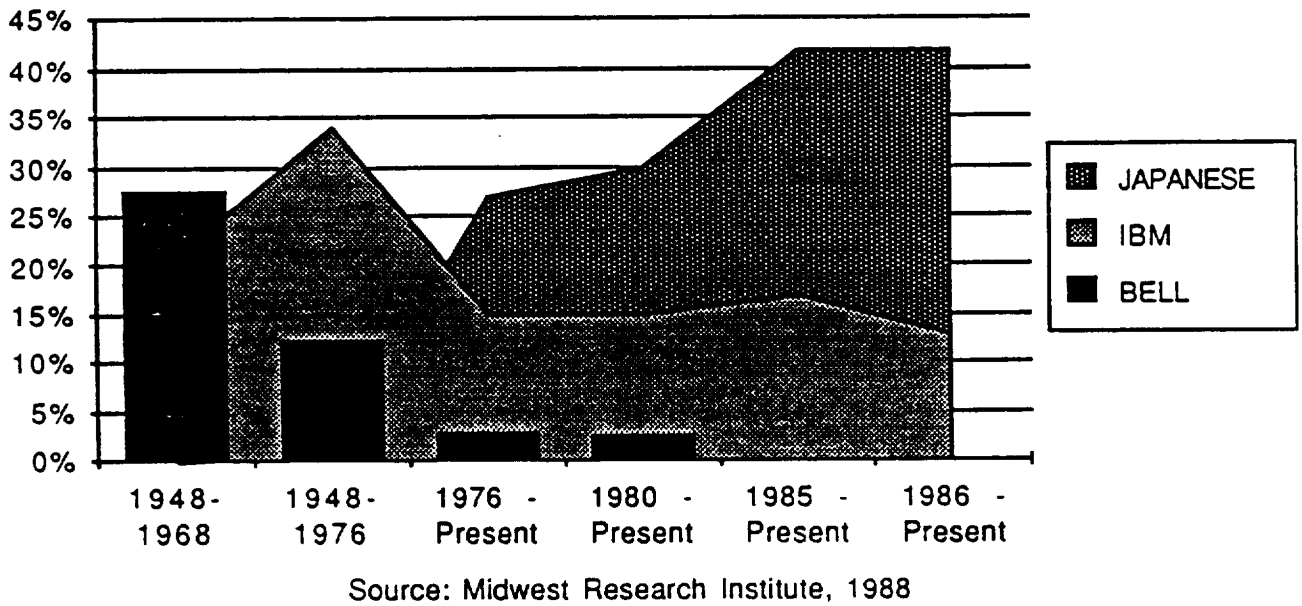

Figure 1. Japanese Share of 455 Key U.S. Patents in Coding Compared to IBM Corporation and Bell Labs From 1948 to Present

[10] Following a review of about 455 key patents in error control coding from 1948 to 1987, calculations were made on 90 percent of those patents whose assignee could be readily determined. While this is admittedly an abridged list to attempt to capture "key" patents, it is the opinion of the research team that the trends derived from calculations using this list would be substantially similar if the entire list were presented.

C. ECONOMIC IMPACT

For the past 30 years NASA has been a driving force in improving digital communications and digital data storage because of its long-term commitment to error-correcting codes. A number of technological developments have occurred concurrently with the progression of error-correcting codes, and all are necessary to achieve today's performance levels. Yet coding has been behind the dramatic rise in industry performance in recent years as well as the decrease in costs. Each time an error-correcting code is made better, storage media, transmission power, and components can be made less expensive.

Through NASA's massive technology transfer and university cooperative programs, all of the error control coding breakthroughs made at NASA and by its contractors have been generally available to a new generation of engineering students. In turn, they have boldly applied coding technology, both in this country and abroad, to more and more capable and powerful electronic devices. Most of these devices use error-correcting code strategies that were demonstrated for use by NASA at least five years prior to any commercial introduction.

Based on industry trends, those electronics products that do not yet have the need for sophisticated error control methods are probably more expensive than is required. Competition may require those products to utilize error-correcting codes in the near future. Some familiar consumer or industrial electronic devices that make use of error-correcting code technology are:

- Compact disk audio systems
- Compact disk read-only memory
- CD-I (compact disk interactive)
- Optical data storage
- WORM optical storage
- Erasable optical storage
- Digital audio tape
- New-generation facsimile machines
- New-generation modems (e.g., 9,600 baud and above)
- High end magnetic disk (hard disk drives)
- Mobile satellite communications

The total market for these products is growing substantially (see Table 4). From a relatively small market of $4.4 billion a year in 1986 (during which time not all of these devices utilized error-correcting codes), these products will account for over $17 billion in annual U.S. sales by 1990 and use a variety of error control coding technologies, the advancement of which can be traced to NASA research and development.

TABLE 4

COMMERCIAL USE OF ERROR-CORRECTING CODES (Sales in $ Mil)

	1986	1988 (est.)	1990 (est.)
CD Players[a]	346	457	658
CD Disks[b]	750	3,276	2,800
CD-ROM Drives[e]	80	150	150
CD-ROM Disks[d]	14	1,740	2,500
WORM Drives[c,i]	20	500	1,031
Erasable Optical Disk Drives[c]	0	9	156
CD-I Drives	0	0	NA
CD-V (Video Disk Players)[e]	48	72	111
DAT Drives[e]	0	20	39
Facsimile Group 3 (Digital)[e]	154	230	359
Facsimile Group 4 (Digital)[j]	0	0	300
Modems (High-Speed)[e,f]	90	176	345
Hard Disk Drives[e,g,h]	2,923	5,233	8,100
Mobile Satellite Terminals[k]	NA	NA	500
TOTAL	4,425	11,863	17,049

[a] *Electronics*, "1988 U.S. Market Report," January 7, 1988, p. 85. (NOTE: The CD boom has put a tremendous emphasis on the sale of components, e.g., speakers, tuners, etc., which are not included here. Sales of these components are projected to be in the area of $1.5 billion in 1988.)

[b] *Chem Week*, December 1987, and *Predicast's Forecast* data base growth rate.

[c] *High Technology*, "Optical Memories Vie for Data Storage," August 1987, p. 45, and September 1987 Freeman Report.

[d] *Computing*, May 28, 1987, p. 16.

[e] *Electronics*, "1988 U.S. Market Report," January 7, 1988, pp. 63-100.

[f] *Communications Week*, September 7, 1987, and *Predicast's Forecast* data base.

[g] *Predicast's Forecast* data base growth rate.

[h] *Business Week* Industrial Edition, November 2, 1987, p. 142.

[i] Private Communication, The MAXTOR Company, August 1988.

[j] The Canon Corporation, telephone interview with Keith Taylor, Marketing Manager, August 30, 1988.

[k] *High Technology*, December 1986, p. 38.

CHAPTER III. CIVIL AERONAUTICS PERFORMANCE AND EFFICIENCY

A. INTRODUCTION

From its establishment in 1915, the National Advisory Committee for Aeronautics (NACA) provided basic research results and advanced aeronautical technology of use to industry and the Armed Forces. When the National Aeronautics and Space Administration (NASA) came into being in 1958, NACA's research, development, and demonstration responsibilities were incorporated into the new organization. For more than seven decades, the goal of this aeronautics research effort has been to maintain the technical performance of American aircraft preeminent throughout the world.

NASA has retained its unique ability to carry out national R&D programs by providing independent, objective, and technical consultative services for U.S. industry. Its programs can aim far into the future to conduct research and demonstrate technological feasibility that would be far too risky and expensive for a single company. The results of all NASA investigations, with the exception of classified military research, are widely offered through documents, seminars, and work in cooperation with industry so that new technology may be used. This process of development, demonstration, and innovation of new technology has far-reaching economic benefits not only for the companies that choose to develop research findings, but also for the national economy and the general population.

This chapter summarizes a series of research advances aimed at enhancing the performance and efficiency of civil aircraft. The cases illustrate the complex paths by which new knowledge applicable to the design, construction, and operation of modern aircraft comes into being; the interactions between the aerospace industry and government centers of research and technology; the numerous evolutionary changes and improvements that are contributed from many sources; and the often prolonged period of time required to validate, demonstrate, and refine technological advances before they become accepted commercially and widely used.

B. RESEARCH AND DEVELOPMENT IN CIVIL AVIATION

NASA's R&D in civil aviation performance and efficiency has been extensive and far-reaching. As an illustration, MRI researchers selected for further analysis representative technical advances in each of the three principal fields that have contributed to modern aircraft advancements. These fields are aerodynamic drag reduction, aircraft propulsion, and flight control technology.

1. Technical Advances in Civil Aviation Prior to 1970

To provide perspective on the technical advances that make possible the air transportation system of today and tomorrow, it is useful to recall the status of civil aviation for an earlier generation.

A particularly useful benchmark is provided by the joint NASA/Department of Transportation study of Civil Aviation Research and Development policy (CARD) conducted in 1970. A principal finding of the CARD study was that over the period from 1945 to 1969, the performance of civil aircraft had improved substantially. These improvements were related to the technical advances derived from the R&D effort. Aircraft speed had increased from 200 to 550 miles per hour; range had increased from 2500 miles to over 5000 miles; and payload capability had more than doubled. Improvements had also occurred in comfort and safety; and operating costs for aircraft had remained constant or decreased slightly over the period, although the price of aircraft had increased.

In the course of analyzing the R&D history, over 400 technological improvements were identified. These represent basic advances or other engineering developments resulting from aeronautical R&D. By the end of 1969 about 200 of these technical advances had been applied to civil aviation (see Table 5). Among the most important advances for civil aviation were the introduction of the swept wing and gas turbine engine, both of which were derived from wartime development of military aircraft.

TABLE 5

SUMMARY OF THE UTILIZATION OF TECHNICAL ADVANCES IN CIVIL AVIATION

Development Date	Date of Introduction								
	Pre-1945	1946-1948	1951-1953	1955-1957	1958-1960	1961-1962	1964-1967	1967-1969	Not Applied
Pre-1945	29	19	10	8	24	8	10		24
1945-1950		1	3	13	41	6	7		35
1951-1955				1	28	17	16	1	33
1956-1960					1	6	29	6	58
1961-1965							17	8	59
1966-1969							1	2	29

For purposes of historical analysis, technological improvements relating to aviation can be categorized in the following areas:

Aerodynamics. The science that treats the motion of air in relation to the aircraft—generally including the effects of external aircraft configuration, airfoils, and control surfaces, sonic boom, etc.

Propulsion. The means of propelling the aircraft, including inlets, engines, propellers, internal flow, exhaust, pollution effects, noise, fuels and lubricants, etc.

Structures. The aircraft structure, including methods of designing and constructing, use of materials, effects of sound on structures, and the engineering analysis of structures.

Avionics. The instruments, communications equipment, navigation equipment, test equipment, radar, etc., that utilize electrical/electronic technology.

Flight Mechanics. The motions that the aircraft undergoes in flight, including methods of representing them for analytical design, pilot training, or similar purposes.

Safety. Devices, procedures, and activities designed for safe aircraft operation, accident avoidance, and crash protection.

Human Factors. The factors in the man-machine interface and human performance that must be considered in aeronautics, including instrument display, flight crew workload, oxygen requirements, etc.

Other. Activities or developments which do not appear to fall easily into any of the above categories.

2. Technical Advances Since 1970

In order to identify the significant technical advances that have contributed to improved performance and operating efficiency of modern transport aircraft, MRI conducted interviews with engineers and designers from major aircraft and engine manufacturers. Similarly, MRI surveyed the opinions of scientists and engineers at each of NASA's major centers of research and technology development, regarding areas in which advanced technology had improved current and proposed commercial aircraft.

The consensus of these experts was that over the period 1970 to 1988, there were three principal technical fields that contributed to modern aircraft advancements:

- Improved aerodynamics/reduced drag
- Propulsion efficiency
- Aircraft flight and engine controls

The newer technical developments that have been incorporated into aircraft of recent vintage are summarized in Table 6. Virtually all of these engineering advances are traceable to fundamental studies by NASA researchers and contractors, and to years of cooperative development by airframe and engine producers working with NASA. The new technologies incorporated in aircraft engines over recent years are summarized in Table 7.

C. AERODYNAMIC DRAG REDUCTION

The technologies MRI chose as representative of aerodynamic drag reduction are the supercritical wing, high-lift systems, and winglets.

1. Supercritical Wing

The profile of the supercritical wing is radically different from the conventional airfoils found on older transport aircraft--and wing shape is perhaps the most fundamental characteristic of an aircraft design. This innovation, derived from NASA research, enables today's transports to fly at speeds of 550 mph rather than being limited to about 450 mph, and to fly more efficiently, with reduced drag and freedom from aerodynamic buffeting.

Basically, the profile of all supercritical wings is characterized (Figure 2) by a substantially reduced (flatter) curvature of the midchord region of the upper surface, a leading edge having a larger-than-usual nose radius, a thicker section at midchord, and increased camber near the trailing edge.

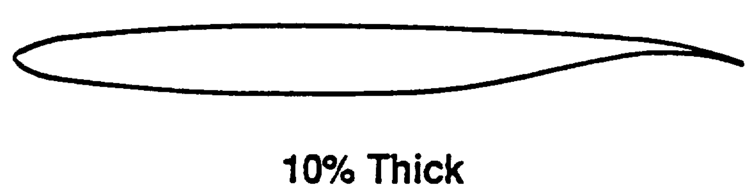

Figure 2. Supercritical Wing Design

TABLE 6

NEW TECHNOLOGIES IN ENGINES

Firm Engine Designation	IAE[a] V2500	GE[b] 36	GE[b] CF6-6/50	CFM[c] 56	MTU[d]	P&W-Allison[e] 578-DX	P&W[e] 2037/2040	P&W[e] 4000	P&W[e] JT8D	P&W[e] JT9D
Basic Technologies										
HIGH-BY-PASS	○		●	●			●	●	●	●
ULTRA-HIGH-BY-PASS (UHB)		■			■	■				
VERY-HIGH-BY-PASS (VHB)	■							■		
Subsystem Areas of Improvement										
COMBUSTOR			●				●		●	●
COMPRESSOR			●				●			
BLADE & VANE SHAPES			●						●	●
TIP SEALS			●						●	●
EXHAUST			●				●			●

[a] Internationale Aero Engines
[b] General Electric
[c] CFM International
[d] Motorem-und Turbinen-Union
[e] Pratt & Whitney Aircraft

● - In production
○ - Initial delivery
■ - planned derivative or developmental

Sources: Aviation Week & Space Technology, McDonnell Douglas, Boeing, NASA.
List technologies confirmed, to date.

TABLE 7

NEW TECHNOLOGIES IN CURRENT OR PLANNED AIRCRAFT

Technology	McD-D MD80/87	McD-D MD-11	McD-D MD-11x	McD-D MD91/92	McD-D C-17	Beech Starship	Boeing 757-200/300	Boeing 767-200/300	Boeing 737-400	Boeing 747-400	Boeing 7J7	Airbus A320/A330
Aerodynamics												
Relaxed static stability		●	●									
Winglets		●	●			●				●		
LEBU's - nacelle	●	●	●									●
fuselage	●											
Airfoil improvements				●		●	●	●		●		●
Supercritical wing			●		●							●****
Surface blown lift *					●							
Vortex generators						●						
Improved wing-to-body fairings	●		●							●		
Low drag nacelle	●	●	●	●			●	●		●		
Propulsion												
UHB (UDF, Propfan)				●							●	
High By-Pass	●	●	●		●		●	●	●	●		●
Digital Electronic Engine Control **		●	●		●		●	●		●		●
Controls												
Glass Cockpit	●***	●***	●***	●***	●***	●	●	●	●	●	O***	●***
Flight management system						●	●	●	●	●		
Engine indicating & crew alerting system						●	●	●	●	●		
Navigation						●	●	●	●	●		
Guidance						●	●	●	●	●		
Engine thrust						●	●	●	●	●		
Attitude direction indicator						●	●	●	●	●		
Horizontal situation detector						●	●	●	●	●		
Windshear detection							●	●	●	●		
Digital Fly-by-wire (DFBW)			O								O	●****
Digital Fly-by-light (DFBL)			O								O	
Active controls					●							
Longitudinal static stability					●							
Air data / inertial reference system											O	
Side stick control			O	O							O	●
Materials												
Composite wet tail		●	●							●		
Lithium aluminum		●	●									
Aramid reinforced aluminum					●							
Epoxy / graphite						●	●	●				
Aluminum alloys (2000 & 7000 series)							●	●		●		
Carbon brakes							●	●		●		
Graphite kevlar								●				
Composite materials (unspecified)		●	●	●	●	●				●		●
Control surfaces		●	●	●	●	●	●	●		●		●
Structural		●	●			●						

* Blown flaps powerlift
** Power-by-wire
● Committed
O Planned
*** Details unknown
**** Partial

Sources: Aviation Week & Space Technology, Flight International, McDonnell Douglas, Boeing.
Lists technologies confirmed to be committed or planned for specific aircraft.

It is clear that NASA's contribution to the supercritical wing extends far beyond discovery of the original concept. The value of proof of concept through a series of flight verification programs cannot be overestimated. In addition, NASA researchers and contractors:

- Collected the extensive data base on supercritical airflow.
- Developed new computer programs to permit analyzing the flow over supercritical airfoils.
- Demonstrated through flight programs that supercritical wings actually provided high performance for commercial transports.
- Developed codes for the systematic design of supercritical airfoils.
- Created several entire families of advanced airfoil sections, such as that used on the new C-17 military transport.
- Eventually brought analysis and prediction together with wind tunnel and flight measurements, thus basing empirical technology on well-understood theory.
- During the Energy-Efficient Transport program, airfoils were incorporated into transport aircraft designs that satisfied airline requirements for good cruise performance and high lift.

Throughout the 24 years that have elapsed since the supercritical idea was born, industry and NASA have worked together to refine and hone a controversial concept into an efficient transportation technology.

It is difficult to imagine the full economic impact that adoption of supercritical wing technology is having on aircraft manufacture and on operations of commercial airlines. NASA conducted research, wind-tunnel tests, and flight validation programs over the 1964-1975 period. Aerospace contractors carried out work to refine the concept and tailor supercritical airfoils to the requirements of modern wide-body transport aircraft over a similar length of time through the mid-1980s. Today virtually all large commercial transports being designed in the United States and foreign countries will rely on wing designs that trace their lineage directly back to what is known as the Whitcomb supercritical wing.

2. High-Lift Systems

The aircraft industry and airline operators could not exploit potential benefits from advanced, efficient wing shapes unless the aircraft were equipped with devices that provide sufficient lift at lower speeds for safe takeoff and landing. In aircraft design, important constraints between high-speed cruise and the low-speed takeoff and landing conditions force the designer to incorporate some form of high-lift device to improve the lift at low speed. For many years this has been accomplished by altering the wing section shape over the inboard part of the wing. Leading edge slats, trailing edge flaps, slotted sections, Fowler flaps, and Kreuger devices have long been employed to reduce takeoff and landing distances, and to allow the aircraft to carry its required payload at takeoff. A typical cross section of multielement airfoils for high-lift is shown in Figure 3.

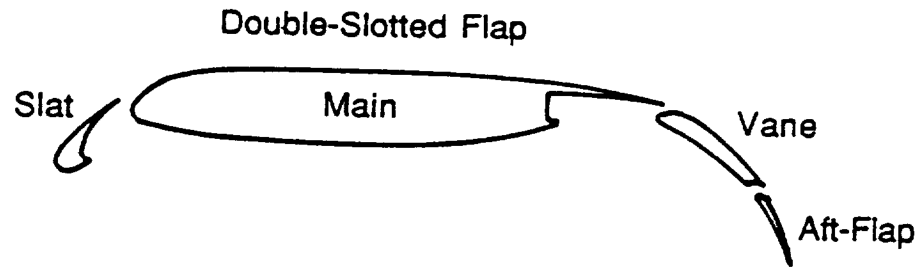

Figure 3. Multielement High-Lift System

Early test flights of NASA's supercritical wing designed to represent wings for commercial transport aircraft showed dramatically the necessity for developing high-lift systems for these newer airfoils. Since the early 1970s, NASA's program to better understand high-lift devices and promote development of superior multielement airfoil systems for transport aircraft has resulted in significant improvements in theory, design techniques, and test methods. All of these contributions are marked by three characteristics: (1) continuing incremental advances in aerodynamic analysis; (2) close and continuous involvement between industry engineers and NASA researchers; and (3) achievement of practical systems that employ deceptively simple changes, yet yield important economic benefits.

Among the significant technical advances in aerodynamic modeling and analysis of multielement high-lift systems, the following developments are particularly noteworthy:

- Mathematical model for two-dimensional multicomponent airfoils in viscous flows
- Viscous/potential flow interaction analysis method
- Nonlinear distributed vorticity method
- Evolution of the NASA/Lockheed multielement airfoil computer program
- Two-dimensional separated wake modeling (SASS) and inverse boundary layer technique
- Development of panel methods
- Direct/inverse methods for synthesis of high-lift systems (TAMSEP)
- Finite field-panel approach for computing potential flow
- Interactive boundary layer procedure with wake

One pioneering approach to high-lift or multielement airfoil analysis was developed by Goradia and his coworkers at Lockheed-Georgia under the sponsorship of NASA Langley Research Center.[1] This program was among the first attempts at analyzing the complex viscous flow about slotted airfoils and has received worldwide distribution and usage. A unique feature of this multi-element airfoil program was the model of the confluent boundary layer flow.

A number of NASA contracts with private companies such as Boeing and McDonnell Douglas further explored new high-lift systems for advanced aircraft. This work on high-lift systems used the newly developed analytic and design techniques, with tests conducted at Langley and Ames. For example, one slightly unconventional design, a leading edge slat, with an advanced large-chord vane and small-chord aft flap was chosen as representative of modern high-lift systems for detailed testing at high Reynolds numbers in the Langley low-turbulence pressure tunnel.[2]

Over the past 18 years, industry and NASA investigators have achieved impressive advances in the art of high-lift design. What was previously empirical cut-and-try has become predictable and rational.

Engineers can develop advanced high-lift sections and proceed to wind-tunnel testing virtually assured that aerodynamic characteristics will be close to those desired. Thus the time and cost to create and certify new high-lift systems have been drastically reduced. Savings in the design and engineering process for a single new aircraft system can easily exceed $2 million.

The major impacts of improved knowledge governing high-lift systems have been the contributions to aircraft performance. Modern airfoil sections provide:

- Ability to exploit cruise-efficient high-aspect supercritical and aft-loaded wings.
- More than adequate low-speed lift and favorable pitching moments at conservative angles of attack.
- Simpler aerodynamic designs that reduce low-speed drag and substantially improve L/D ratio.
- Simplified mechanical systems having reduced maintenance requirements.
- Increased takeoff payload and extended range.

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[1] W. A. Stevens, S. H. Goradia, and J. A. Braden, "Mathematical Model for Two-Dimensional Multi-Component Airfoils in Viscous Flows," NASA CR-1843, July 1971.

[2] Harry Morgan et al., "A Study of High-Lift Airfoils at High Reynolds Numbers in the Langley Low-Turbulence Pressure Tunnel," NASA TM-89125, July 1987.

- Reduced fuel consumption (about 4 percent) during takeoff, climb, descent, and landing (up to 50 percent of many flights).

- Shorter takeoff distance, better climb, and reduced airport noise levels.

The benefits from improved reliability, greater safety, and environmental concerns are significant though hard to measure. Aircraft equipped with advanced lift systems can routinely meet the stringent regulation for operation into airports which have flyover noise restrictions.

3. Winglets

The concept of winglets represented a clean breakthrough in drag reduction. The value to commercial aviation was obvious in an age of rapidly rising fuel prices, the structure of winglets was straightforward, and conventional aerodynamic principles could be used to design the airfoils. Best of all, NASA could conduct direct and realistic tests of the new idea. Various models could be explored in wind tunnel tests, and wing tips of existing aircraft could be readily modified for flight tests.

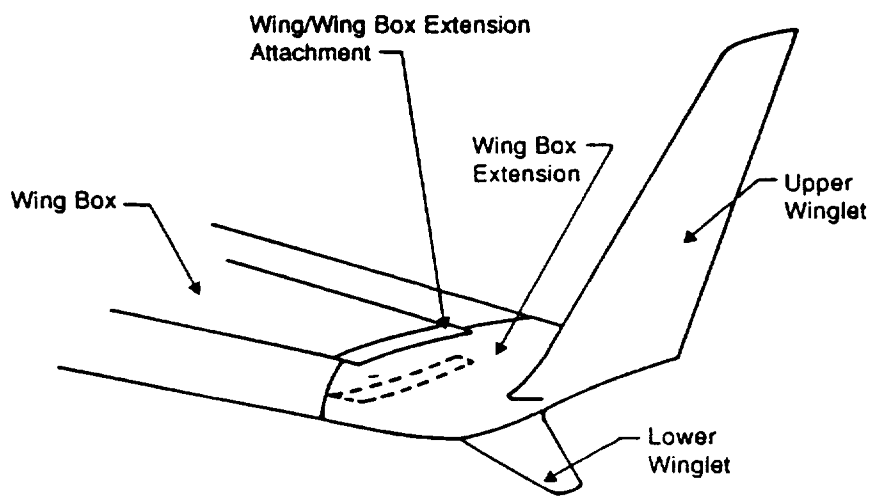

Figure 4. Typical Winglet Design

The inclined "jibsails" now appearing on the tips of commercial transport aircraft are perhaps one of the most visible examples of NASA-developed technology. Winglets were first developed by researchers at Langley in 1974 as a promising means of reducing lift-induced drag. These new, nonplanar airfoils could significantly reduce fuel consumption, increase aircraft range, and cruise smoothly and efficiently—all with few apparent drawbacks. There was some initial reluctance to accept the concept of airfoils at the end of wings as a drag-reducing technology, because somewhat similar "end plates" had been evaluated for over 50 years and were regarded as impractical. Langley's Dr. Richard T. Whitcomb contributed the key observation that had been overlooked for so long. To be effective, winglets must be aerodynamically shaped to provide sufficient side forces to overcome drag. Simple end plates could not provide the necessary forces.

NASA researchers conducted numerous wind-tunnel experiments to confirm and validate the mechanism by which winglets operated to reduce drag. Both NASA and the aircraft makers carried out extensive developments to optimize the performance of essentially simple airfoil designs. The earliest commercial acceptance of winglets was on the Learjet in 1979, only five years after the concept was discovered.

Boeing adapted NASA's winglets for use on the KC-135 tanker transport and demonstrated the value of incorporating winglets for use on large aircraft of the B-707 class. The U.S. Air Force acknowledged the improved performance that winglets could provide for the KC-135 but reluctantly concluded that it would not be feasible to retrofit its entire fleet of tankers.

Douglas Aircraft under NASA contract performed a 200-hour flight test program to select the most favorable configuration for winglets on the DC-10.

The benefits of winglet technology were so obvious and compelling that foreign aircraft producers soon adopted what has come to be known worldwide as "the NASA winglet." Airbus A-320 became the first commercial air transport to sport winglets. The newly redesigned Boeing 747-400 that will fly in 1988 is the newest U.S. aircraft to make use of winglets. McDonnell Douglas has incorporated winglets on their advanced MD-11 transport. At least 30 different aircraft from China, Israel, the U.S.S.R., Europe, and the United States currently fly with the aid of winglets.

On commercial airliners, the simple addition of a properly designed winglet is estimated to save at least 3 percent of fuel burned, provide 2 percent greater range, and give a 5 percent reduction in takeoff distance.

D. AIRCRAFT PROPULSION

The most significant benefits derived from improved aircraft performance and efficiency have been due to advances in propulsion technology. Relatively small improvements in the propulsive efficiency of aircraft engines result in dramatic savings in fuel cost and in reduced operating and maintenance costs for the airlines.

Improved aircraft performance resulting from advanced propulsion has made air travel more attractive, convenient, cheaper, more comfortable, and productive, while reducing noise and air pollution emissions. The superior performance and efficiency of advanced technology engines developed in the United States permit them to dominate the worldwide market for aircraft engines--resulting in 1987 engine revenues of $15.9 billion.

Many important technical advances in aircraft engines are directly associated with NASA research and development programs carried out since 1970. The major programs that have resulted in technology that is being used commercially include:

- REFAN program to develop a high-bypass fan jet engine to achieve reduced aircraft noise.

- Three elements of the Aircraft Energy Efficiency program (ACEE):

  Engine Component Improvement program (ECI) to develop specific components that would improve jet engine performance

  Engine Diagnostics program to define the causes and extent of engine performance deterioration and the Nacelle Aerodynamics and Inertial Loads (NAIL) program to monitor loads that result in engine wear.

  Energy-Efficient Engine (EEE) to develop two new engines designed to maximize energy efficiency

- Engine Hot-Section Technology (HOST) to develop more durable structures for the high-temperature zones and methods to predict degradation of engine performance or to restore efficient performance.

NASA's aircraft engine development programs carried out over the period 1970 through the late 1980s were destined to lead to the generation of jet engines that were clean, quiet, and fuel-efficient; required less maintenance; and cost less to own and operate.

1. The REFAN Program

As the 1960s drew to a close, turbofan engines were replacing the older turbojet aircraft engines. Air bypass ratios (the proportion of air flowing around the turbine relative to that passing through the combustor), however, were still quite low. By far the most widely sold engines in the world at that time were Pratt & Whitney's JT3-D and JT8D-9. The relatively newer General Electric turbofan boasted what was then considered a relatively high-bypass ratio. NASA's engine studies pinpointed the urgent need for the next few years: an affordable retrofit for thousands of older jet engines that could upgrade performance through high-bypass technology.

One of the major problems confronting civil aviation was the noise and smoke generated by aircraft in the vicinity of airports. The noisiest aircraft in the commercial fleet were the standard-bodied aircraft introduced into service through the 1960s. These aircraft consisted of the 707s, 727s, 737s, DC8s, and DC9s powered by Pratt & Whitney turbofan engines. These aircraft comprised the majority of the existing and projected fleet so that a significant reduction in the noise levels from these aircraft would result in a major reduction in airport noise exposure.

The purpose of NASA's REFAN program, initiated in August 1972, was to demonstrate the technical feasibility of substantially reducing noise levels by retrofitting existing aircraft with quieter REFAN engines and new acoustically treated nacelles.

Phase I contracts were let for design and analysis of the engine and nacelle modifications with three major contractors: Pratt & Whitney Aircraft, Boeing Commercial Airplane Company, and the Douglas Aircraft Company. Additional contracts were undertaken by American Airlines and United Airlines for consulting work to ensure that the modifications being considered incorporated as many of the user airlines' requirements as possible.

The ultimate goal of the REFAN program was to develop engine and nacelle retrofit kits for standard-bodied aircraft. Engine and airframe modifications were limited to those changes that would make the engines quieter. For the engine, the changes were limited to the fan (including fan stage and static parts), the fan drive turbine, exhaust nozzles, and engine nacelle with acoustic treatment.

While improved engine performance and efficiency were not primary objectives of the REFAN program, it is interesting to note that the higher-bypass engine showed significant improvements in thrust both at takeoff and cruise, an impressive 22 percent reduction in takeoff field length, and a worthwhile reduction in specific fuel consumption (exceeding 2 percent).

Eventually more than 500 such aircraft were retrofitted with the REFAN engine at a cost of $1.338 million each, with about an equal split between engine and aircraft.

Partly as a result of the REFAN program, the significant benefits from high-bypass ratio turbofan engines became widely recognized. American Airlines, for example, installed hundreds of the new, large-diameter, high-bypass turbofans and coined the name "whisper-jet." Other airlines followed suit, and today quiet high-bypass fan jets characterize the propulsion system for most commercial transports.

The REFAN program proved so successful that Pratt & Whitney continued the development and financed entirely with company funds the JT8D-209 engine, which they hailed as "the first REFAN."[3] The retrofitting of refanned engines to upgrade older aircraft has remained an attractive option for aircraft owners. Today, several years after production of the 727 ceased, owners of the 727 and 737 aircraft can modernize their fleet by the installation of high-bypass turbofan engines.[4] In the 15 years since the REFAN program was initiated, the cost of reengining the 727-200 has increased to $8.6 million. The increased performance and fuel efficiency of the modernized REFAN represent an attractive investment for the owner over the extended life of the aircraft. The essential objectives, accomplishments, and impacts of NASA's REFAN program are summarized in Table 8.

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[3] "JT8D-209 the First Refan," *Flight International*, February 18, 1978, pp. 428-430.

[4] Graham Warwick, "727 Renewed," *Flight International*, August 15, 1987, pp. 26-27.

TABLE 8

REFAN

• **CONTRACTOR**	Pratt & Whitney (Boeing, Douglas)
• **PROBLEM**	Reduce jet noise, smoke
• **OBJECTIVE**	High bypass for JT8D
• **RESULTS**	50-inch titanium fan Sound-absorbing cowl Nacelle, pylon, and mount First "Refan" JT8D-109
• **IMPACTS**	Reduce noise by 7 db (t.o., 11 db (approach) 14% greater thrust 500+ aircraft refanned @ $1.338 mil. "Whisper-jet-era

2. Three Aircraft Energy Efficiency Elements

a. Engine component improvement (ECI). The Arab oil embargo of 1973 and the sharp fuel price increases that followed dictated an urgent new priority for NASA's research programs: fuel-efficient engines. In August of 1974 NASA embarked on the near-term development of improved engine components that could reduce by 5 percent the fuel burned by jet engines. NASA planned to invest approximately $25 million in this program, recognizing that a 5 percent reduction in fuel consumption would result in roughly $500 million annual fuel savings.

The first task was to screen the field to determine which component improvements would offer the greatest economic benefits. NASA awarded contracts to engine makers General Electric and Pratt & Whitney, aircraft makers Boeing and Douglas, and airline operators Transworld Airlines, United Airlines, American Airlines, Pan American and Eastern Airlines to propose those engine modifications that would provide the greatest benefits. From this industrial input came an astonishing list of more than 150 proposed engine improvements; General Electric proposed 58 engine modifications while Pratt & Whitney suggested 95 engine components for improvement. NASA and the airline operators evaluated these suggestions and narrowed the list to 29 component improvements that would offer the greatest near-term benefits.

The economic impact of each engine improvement was calculated in terms of incremental net yearly savings. Boeing, Douglas, and American Airlines prepared independent economic evaluations that included aircraft fuel, insurance, and maintenance costs, and the cash outlay for engine and aircraft modifications.

Based on this economic assessment, 16 engine component improvements were selected for development. See Table 9.

TABLE 9

ECONOMIC RANKING—HIGH PAYBACK IMPROVEMENTS

Concept	Cruise SFC Reduction (%)	Payback Period (Years)	ROI (%)	Cumulative Fuel Savings Through 2005 (Million Gallons)
GE CF6				
Fan improvement (blades and stiffeners)	1.8	0.8	67-123	1,056
HPT aerodynamics	1.3-1.6	0.2	600	296
HPT roundness	0.4	0.8	140	398
Front mount	0.1	0.6	165	70
Short core exhaust nozzle	0.9	0.01	8,713	411
HPT active clearance	0.7-0.9	4.4	21	242
LPT active clearance	0.3	4.1	23	92
P&W JT9D				
Fan technology	1.3	1.3	--	70
Ceramic thermal barrier coating	0.2	0.05	--	259
HPT active clearance	0.65	1.4	--	468
HPT ceramic outer air seal	0.4	0.5	--	516
JT8D				
HPT blade cooling	1.8	0.04	--	259
HPT outer air seal	0.6	3.9	--	90
Abradable tip seals	0.9	1.4	--	589
Douglas				
DC-10 cabin air recirculation	0.8	1.2-1.6	64-87	85
Thrust reverser fairing	1.2	--	--	--

Because of the likelihood that the ECI technology would be incorporated in near-term derivative commercial transport engines, NASA had recoupment provisions in the contracts with industry for 1 percent of the gross receipts on the sale of parts and engines which incorporated the improved parts derived from the ECI-funded research, up to the $24.3 million NASA investment. To date, the government has recouped almost $12 million from the users of the ECI technology.

The improved technology developed through NASA's engine component improvement program was introduced into engines and aircraft beginning about 1978. Through fuel savings and reduced direct operating costs, airline operators have recovered many times the initial cost of implementing these improvements. Through royalty payments based on the sale of equipment incorporating these components, NASA has recovered most of its initial research investment.

By 1982 most of these improved components were flying and saving fuel, giving aircraft companies a firm leg up in the commercial aircraft marketplace where they are increasingly being challenged by foreign competitors. Market projections indicate that all 16 concepts combined will result in saving more than 5 billion gallons of fuel over the expected life of the improved engines.

b. Energy-efficient engine program (E^3). When the Aircraft Energy Efficiency program was established, NASA's earlier projects for a "fuel-conservative engine" were incorporated and the program rechristened Energy Efficient Engine (EEE or E-cubed for short). This was a classic NASA program designed to provide an advanced technology base, first by proving new concepts, and then by testing and evaluating them under realistic conditions. The EEE program sought to provide technology for a new generation of fuel-efficient turbofan engines that could be ready for service by 1984.

NASA's goals for the EEE relative to the then current turbofans were:

- Reduce fuel consumption (SFC) by at least 12 percent
- Reduce performance deterioration by at least 50 percent
- Reduce direct operating costs (DOC) by at least 5 percent
- Meet future FAA noise requirements and EPA exhaust emission standards

By 1976, when the EEE program began, turbofan engines had become more efficient and had largely replaced earlier turbojets developed in the 1950s and low-bypass fan engines designed in the 1960s. The essential feature of all turbofan engines is an extra set of fan blades ahead of the working core of the engine. This fan, driven directly by power from the turbine, propels the entering air stream partly through the core, with the remainder of the air passing around the core.

High-bypass turbofan engines of the early 1970s offered increased propulsive efficiency. The fans and turbines moved more pounds of air through the engine per unit of fuel burned than earlier jets and low-bypass engines. The air stream is ejected out the engine exhaust nozzle at lower speeds and cooler temperatures. The twin advantages are quieter engines and greater fuel efficiency.

Considerable opportunity existed to develop engines having improved characteristics and even better efficiency. The earliest high-bypass engines had problems with reliability and with deterioration of performance in service. Engines were complex and required more maintenance than was desired. Higher pressure ratios in both compressor and turbines would improve efficiency. Fuel ignition and combustion could be improved, and mixing of hot turbine exhaust with bypass air needed to be more efficient. These were among the areas that NASA sought to improve by encouraging development of technology for an advanced generation of turbofan engines.

Under the EEE program, NASA's Lewis Research Center contracted with General Electric and Pratt & Whitney to take a "clean sheet" approach--to design, build, and test new engines that would incorporate advanced engineering to meet or exceed the goals of the program. The end result would be working engines that would prove new propulsion concepts and permit evaluating the advanced systems technology features. It was never intended that these experimental engines would be ready for production. Incorporation of the best EEE technology into future production engines was left to the engine manufacturers to be accomplished when the technology was sufficiently established, and when the market for advanced fuel-efficient engines warranted. The EEE program extended from 1977 to 1983, and the technology that was developed is helping to produce today's advanced aircraft engines.

Starting about 1983, both Pratt & Whitney and General Electric began to incorporate the technology developed for the EEE program into their new generation of engines. A few of the advances that have been commercialized by Pratt & Whitney in their PW2037 engine are indicated in Figure 5. The progression of advancing technology, leading to improved propulsion efficiency in the even newer PW4000 series of engines is shown in Figure 6.

c. Engine diagnostics, NAIL, and HOST programs. These three NASA research programs are considered together for a number of reasons. Each program sought to reduce the extent to which jet engine performance deteriorated in service, to restore lost performance through proper maintenance, or to develop rugged propulsion systems less prone to performance degradation. Additionally, these programs illustrate how cooperative investigations involving NASA, industry, and universities often lead to technical advances which represent new knowledge and understanding, rather than being embodied in some specific engine hardware. It is important to recognize the economic impacts that derive from improved knowledge.

Engine Diagnostics was made a part of the Engine Component Improvement program in 1976. The goal was to determine the specific causes of engine performance deterioration in new and used General Electric CF6 and Pratt & Whitney JT9D engines, which power the Douglas DC-10 and Boeing 747. Once those factors were determined, design information could be derived to improve both existing and new engines by making them less subject to performance degradation.

Knowledge about engine performance deterioration was general and incomplete. Precisely how various engine sections deteriorate and the rate and extent of performance losses needed to be determined. Under contract with Lewis Research Center, Pratt & Whitney, Douglas, Boeing, and General Electric undertook to document the causes and potential cures for engine performance losses.

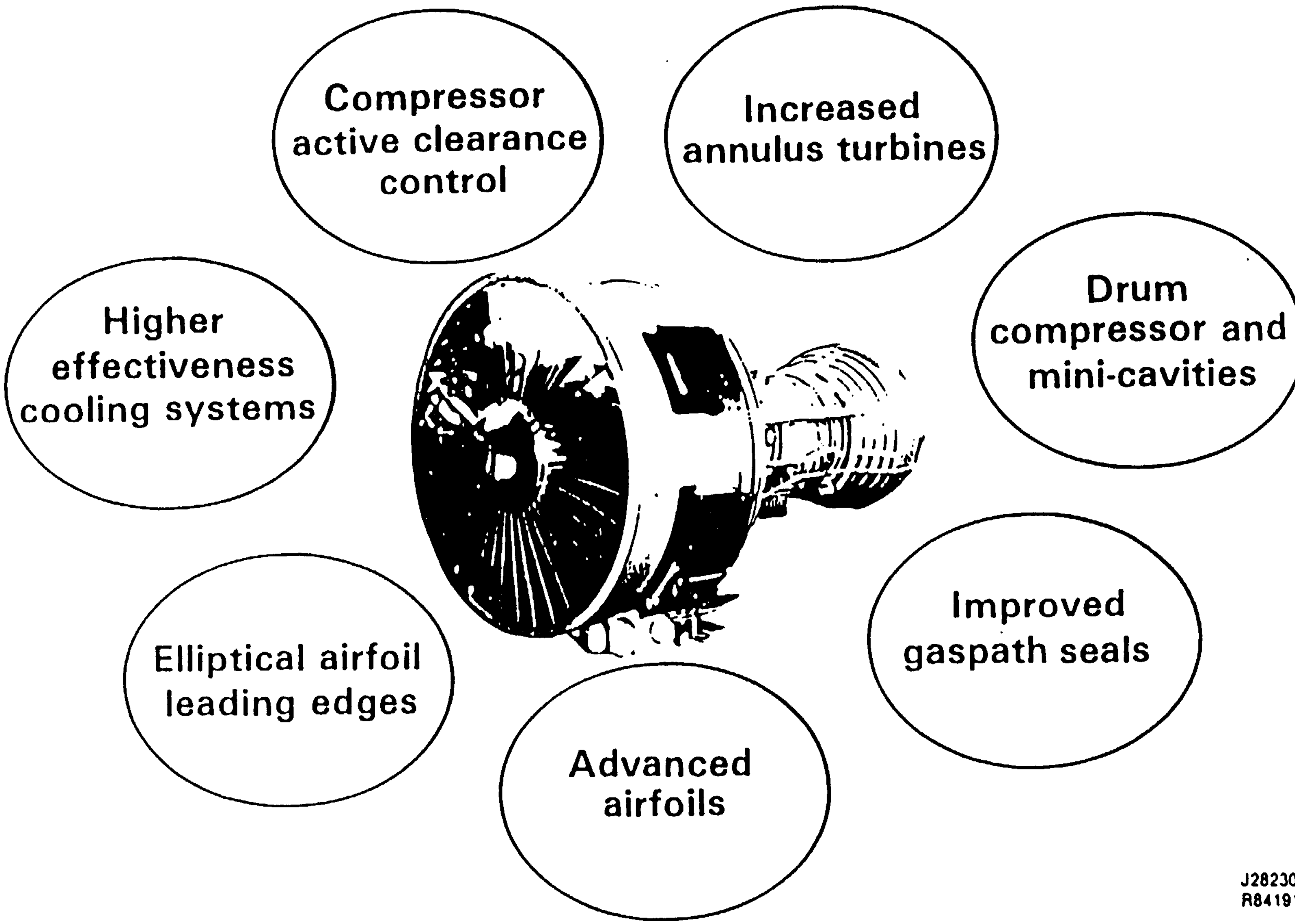

Figure 5. NASA-Sponsored E^3 Technology Utilized in PW2037

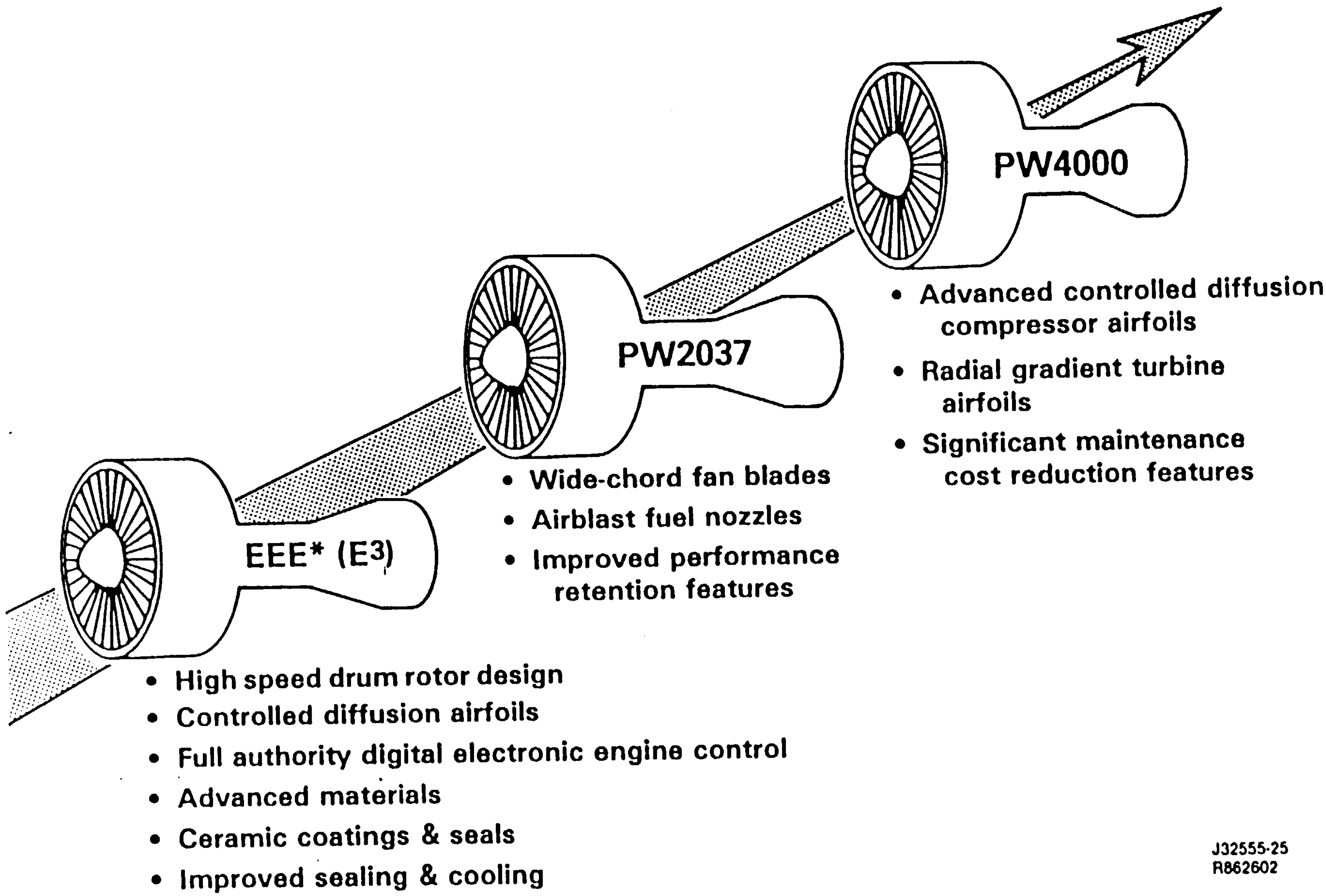

Figure 6. EEE Technology Used in Advanced P&W Engine

Historical data were gathered from airlines representing about one-third of the world's fleet of aircraft. Data from engine testing during manufacture, airplane certification tests, normal flight data, and records from overhaul/repair organizations were collected. Among contractors participating were TransWorld Airlines, Pan American World Airways, Northwest Airlines, and American Airlines.

Data analysis showed that three generic causes of engine performance deterioration were of primary importance:

1. Blade-to-seal rub-induced clearance changes

2. Erosion of fan and compressor airfoils and seals

3. Thermal distortion of hot section parts

An important finding was that significant short-term deterioration occurred during the first few flights conducted by the airframe manufacturer prior to delivery of the airplane to the airlines. This rapid deterioration resulted in an increase of 1 percent in specific fuel consumption. For both the CF6 and JT9D engines, rubs between blades and stationary seals resulted from loads that occurred at high angles of attack during aircraft acceptance tests or in avoidance maneuvers.

Long-term deterioration in service resulted in an additional 2.5 to 3.0 percent loss of performance. Blade tip clearance increases and thermal distortion of turbine parts, plus fan and compressor airfoil erosion/roughness accounted for most of the lost performance.

The Diagnostics Program created an impressive array of instrumentation and engine measurement technology to monitor changes in engine airflow, temperatures, and tip clearances. Laser velocimeters and laser proximity gap measuring probes were first applied to engine measurement. High voltage X-ray techniques were developed to monitor changes in engine clearances.

Results from the engine diagnostics program provided a series of recommended actions that could markedly contribute to performance retention. Modified takeoff procedures by the operators, modular maintenance routines, less severe acceptance testing, and improved tip seal designs could cut performance deterioration by 60 percent.

The follow-on Nacelle Aerodynamics and Inertial Loads (NAIL) program grew directly out of the principal finding of the Engine Diagnostics work. Distortion of the engine case under load was found to be the most important cause of clearance closures and rubs. As a consequence, NASA quickly organized a cooperative program to investigate aerodynamic and inertial loads on the engine nacelle. Boeing provided its No. 1, 747 for instrumented flight tests; Lewis worked with Pratt & Whitney to gather engine data; and NASA's Langley Research Center teamed with Boeing to collect aerodynamic data.

The resulting cooperative NAIL program was highly successful, and flight tests provided dramatic new information. The instrumentation aboard the 747 was impressive: 693 pressure sensors, 30 accelerometers, 12 blade clearance probes and 7 rate gyros were installed. A total of over 700 performance readings were monitored and recorded using this flying laboratory.

It was determined that nacelle aerodynamic (pressure) loads accounted for 87 percent of total short-term deterioration (0.7 percent cruise SFC increase). Inertial loads, which had been suspected as a major cause of turbine and fan deterioration, were responsible for only 13 percent of losses in engine efficiency. An integrated engine and nacelle was designed that greatly reduced aerodynamic loads on the engine cases, minimizing distortion and closure rubs. Use of 20 degrees flap at takeoff of the Boeing 747 (rather than the standard 10 degrees) would further substantially reduce aerodynamic loads on the engine inlet.

Economic analysis showed that (at 1979 fuel prices) it was cost-effective to restore four-fifths of the 2 percent cruise SFC typically unrestored after standard engine repair/overhaul. For the CF6 fleet alone each 1 percent gain in engine performance equals a yearly saving of 35-40 million gallons of fuel.

The engine Hot Section Technology (HOST) program started in 1981 as an eight-year, $50 million study to improve the durability of advanced gas turbine engines. In common with Engine Diagnostics and NAIL, the HOST program sought new understanding of the processes responsible for component deterioration and parts failure in the hot, highly stressed combustor and turbine sections.

One of the problems associated with early high-bypass turbofan engines was poor reliability. It was expected that one in-flight engine shutdown due to component failure would be experienced for every 10,000 hours of engine operation. Through analytical modeling, life prediction systems, design of more durable components, and experimental testing, HOST sought knowledge needed to accomplish a quantum leap toward more durable engines.

Although no specific engine hardware was to be developed, HOST was an extremely broad and multidisciplined effort. A total of 42 distinct research groups (NASA, industry, and universities) tackled projects in six major areas:

Structural Analysis
Fatigue and Fracture
Surface Protection
Combustion
Turbine Heat Transfer
Instrumentation

Major efforts were directed toward improved life prediction methods for creep-fatigue interactions and fracture due to elastoplastic crack propagation. Over 70 investigations were carried out in 21 areas relating to understanding and controlling failure in hot section components. Conferences were held at Lewis each year to ensure speedy dissemination of the rapidly accumulating knowledge about engine failure. A total of 152 technical reports and papers resulted from the HOST program. In a retrospective survey, all participating organizations indicated that directly relevant technology had been developed and that the new concepts were useful in the design of durable turbine elements.

Accurate component life prediction models and 3-D inelastic analytic methods for hot section components provided new approaches to more durable turbine blades, vanes, disks, and to producing combustor liners with markedly increased life expectancy. These concepts are currently having major effects on the materials and structures incorporated in advanced engine designs.

While it is not possible to single out the contribution of each increment of the HOST program, there has been a dramatic improvement in the durability of today's turbofan engines. By 1987, engine reliability and durability had increased so that only one in-flight engine shutdown is experienced for every 50,000 operating hours. This fivefold improvement has great commercial value. Airline operators hasten to point out that their savings due to reduced maintenance requirements are at least as important as fuel savings.

E. FLIGHT CONTROL TECHNOLOGY

Key NASA R&D advances in flight control technology center on digital fly-by-wire flight controls (including active controls, electromechanical actuators, lightweight hydraulics, relaxed static stability, and structural load alleviation); digital engine controls; and integrated aircraft controls (HIDEC).

NASA engineers very early recognized that computer-controlled flight could dramatically enhance the flyability of modern complex aircraft, both military and commercial.

Advantages that were not obvious at the beginning of the fly-by-wire development have surfaced with regularity over the years. Having digital fly-by-wire also enables aircraft to have "active" controls, allowing independent control surface adjustments based on the aircraft's aerodynamic situation rather than pilot input. With such a system, stability can be augmented, and structural loads can be managed and alleviated. Flight control systems can be easily integrated with engine controls and load management controls, giving way to a generation of "smart" aircraft. Drag can be reduced by using smaller control surfaces and static stability--the condition of an aircraft being rigged to exert forces against itself to create hands-off stability--and can be relaxed in order to reduce the significant drag inherent in a static stability design. The advantages of fly-by-wire today include:

- Relaxed static stability.
- Separate surface stability augmentation.
- Active controls.
- Digital engine control integration.

- New aircraft design based on new sets of control laws (such as the futuristic X-29).
- Significant weight and volume savings, especially for larger aircraft.
- Improved airplane-handling qualities and an immunity to structural for control mechanisms to changes such as bending and flexing.
- Easier mating of the basic control system and the autopilot, without adverse interactions often encountered with conventional mechanical systems.
- Reduced vulnerability to battle damage through use of redundant systems, each with independent wiring.

Unfortunately for America's air transport industry, no domestic airframe manufacturer has chosen to build a full-authority digital fly-by-wire airliner. The closest any manufacturer has come is the Airbus A-320. It is, for most purposes, a full-authority, computer-controlled aircraft except that mechanical rudder control is maintained as a backup.

Even though none have ventured beyond partial digital control, domestic airframe companies have been working hand in hand with NASA over the years on digital fly-by-wire controls and the concomitant advantages brought by this technology, such as active controls, relaxed static stability, and separate surface stability augmentation.

One early candidate for experimentation with active controls that used computers and special sensors but not full-authority fly-by-wire was the Lockheed L-1011.

Boeing's 757 designed in the mid-'70s and the 767 designed in the early '80s used fly-by-wire couplings on some spoilers and some aileron control, but stopped short of full-authority fly-by-wire.

With or without fly-by-wire, active controls are available now to major aircraft designers because of NASA's efforts. Digital fly-by-wire greatly simplifies the addition of active controls to an aircraft and allows control management to be merged with structural management.

Relaxed static stability is another by-product of digital fly-by-wire and active controls. Simply stated, it makes an aircraft unstable in flight by design, then makes it stable again by computer-actuated control surface adjustments occurring about 40 times per second.

An additional and equally important addition is digital engine controls, whereby a computer can give simultaneous attention to 10 or more variables, and make up to several adjustments per second. The digital electronic engine control project (DEEC) at Ames-Dryden and earlier work at NASA Lewis turned up a number of other benefits of using digital control, not the least of which was dramatically increased efficiency, up to 40 percent improvement in specific fuel consumption over nondigitally controlled engines.

One of the looming challenges for NASA and airframe and engine manufacturers is the question of integration, making the digital fly-by-wire system totally integrated with management of active controls and "artificial" stability. Additionally, integrating the digital electronic engine controls to allow the engine to respond to certain aerodynamic situations is an area that commercial aircraft manufacturers are just beginning to address.

F. ECONOMIC BENEFITS FROM NASA'S R&D IN CIVIL AVIATION

Economic benefits derived from advanced technology in commercial aircraft are of impressive magnitude. Overall economic impacts are observed primarily in three areas:

- Manufacturing industry in the form of production, value-added, sales, and exports of airframes and engines
- Certificated air carriers in the form of operational savings due to efficiency gains in speed, load, and operational capabilities
- Air transportation system in the form of benefits to users

In discussing the role of technological advances on civil aviation, it is appropriate to recognize three important factors that affect the measurement of economic impacts.

First, the aircraft firms are directly governed by the desires of their customers, the airline companies. This means that they are concerned with cost and cost-related factors including the price of the plane (which includes development costs), direct operating costs, load factor capabilities, and safety.

The second important factor results from the first: U.S. aircraft firms tend to make derivatives rather than entirely new planes because of the tremendous development costs built into the price of the plane. These development costs also make it prohibitively expensive to add only a single new technology, even on a derivative.

And third, NASA's work in aerodynamics, controls, and propulsion has had the impact of developing and verifying concepts and proving the potential of new technologies. But, there has always been a need to refine those tests and technological developments for a particular aircraft (e.g., winglets on the DC-10/11).

With these three givens, the overall economic benefits accruing to the U.S. economy from civil aviation and associated technological advances can be summarized as:

- The U.S. aircraft industry is a major U.S. industry, contributing economic benefits in billions of dollars, with high growth and a positive export position.
- Aircraft efficiency has improved significantly over the past 20 years, both overall and for specific aircraft.

- NASA-sponsored programs have initiated the development, verified the viability, and proven the benefits of many new aeronautical technologies.

- The impact of technological change on civil aviation (a significant portion of which originated from NASA-sponsored efforts) has resulted in millions and possibly billions of dollars saved in fuel consumption and direct operating costs. In addition, these changes have helped increase the growth of air travel as a method of transportation and placed the U.S. aviation industry in a very competitive market position.

Exemplary NASA programs and technologies in the civil aeronautics area include nacelle aerodynamic and inertial load (NAIL) and aircraft energy efficiency (ACEE). In the area of propulsion, NASA programs and technologies include digital electronic engine controls (DEEC), energy-efficient transport (EET), energy component improvement (ECI), energy-efficient engine (EEE), high-bypass engine (REFAN) and hot section technology (HOST). For controls, NASA programs and technology include digital fly-by-wire (DFBW), integrated aircraft controls (HIDEC), and "glass cockpit" (ATOPS).

MRI has developed quantified estimates of impact in four areas: overall impacts, aircraft efficiency, fuel savings, and dollar impacts. Our findings are as follows.

Overall Impacts

- Growth in U.S. aircraft shipments, 8 percent per year since 1970.

- U.S. aircraft firms amassed $22 billion in sales in the first 7 months of 1988.

- Growth in U.S. aircraft engine shipments of 11.7 percent per year since 1970.

- 1988 U.S. aircraft <u>engine</u> shipments estimated to reach almost $17 billion.

- Trade surplus of $10.8 billion in U.S. aircraft industry in 1986.

- Growth of 10.6 percent per year of U.S. airline industry (in revenue passenger miles) between 1950 and 1985.

Aircraft Efficiency

- Reduction in Btu energy consumption per revenue passenger mile of 4.3 percent per year from 1975 to 1985.

- Increase of 3.6 percent per year in revenue passenger miles per gallon of fuel from 1965 to 1985.

- Increase of 4.1 percent per year in available seat miles per hour from 1965 to 1985.

- Increase of 2.9 percent per year in available seat miles per gallon from 1965 to 1985.

- Sevenfold improvement in direct operating costs per available seat mile for small transport aircraft (e.g., DC-9) between the period 1940 to 1983.
- Sixteenfold improvement in average seat miles per hour for small transport aircraft between the period 1940 to 1983.
- Twofold improvement in fuel to payload ratio between the 727-200/JT8D-15 and the A320/CFM56-5.
- Decrease of 30 percent in fuel consumption between the 747-400 and the 747-100.

Fuel Savings

- High bypass engine with electronic engine controls, 7.5 percent fuel savings.
- Winglets, 5 to 7 percent fuel savings.
- Ultrahigh bypass engine 20 to 45 percent fuel savings.

Dollar Impacts[5]

- Change of 1 percent in domestic specific fuel consumption (SFC) is equal to an estimated $17,300 savings per plane per year.
- Change of 1 percent in domestic direct operating costs (DOC) is equal to an estimated $120,000 savings per plane per year.
- Fuel efficiency gains over past 30 years equal an estimated $1.7 billion per year (1965 compared to 1985).
- DOC gains over the past 30 years equal an estimated $13.7 billion per year (1965 compared to 1985).
- 747-400 (with winglets, improved airfoil, low drag nacelle, high bypass engine, digital engine controls, and "glass cockpit") has an estimated $640,000 in fuel saving per year over the 747-100.
- NASA, through the ECI program, funded GE to the level of $10.2 million. This program resulted in engine improvements in SFC estimated to be $15 to $22 million per year.

It is clear that NASA R&D expenditures in civil aeronautics have not only placed the United States at the leading edge of the world's commercial aircraft market but have contributed substantial economic benefits for the U.S. economy as a whole.

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[5] Information for these calculations was provided by Boeing, General Electric, McDonnell Douglas, and U.S. Statistical Abstracts. In each case, conservative data and assumptions were used and all information is for domestic operations. See Volume III.

CHAPTER IV. FUTURE TECHNOLOGY AREAS

A. INTRODUCTION

The final element of MRI's study comprised an examination of potential benefits from emerging NASA technology. New technologies that knowledgeable specialists expect will have important commercial application were selected for analysis. The analysis is intended to complement the more detailed case studies which examined technical advances from NASA R&D that are currently having significant economic consequences.

The emerging technologies described here illustrate the complex process by which new knowledge is converted into useful technology, which in turn through innovation becomes accepted and widely used commercially. It is possible to observe patterns of similarity and differences among the examples given. The process of screening and selection of case examples was relatively straightforward:

- Review typical fields of NASA research and technology development
- Screen for developments regarded as unusually successful and valuable
- Select cases believed by technologists to have the greatest near-term economic potential
- Document NASA's and industry's roles and contributions to the technology

For each of the cases presented, it may be useful to consider:

- What are representative areas of NASA-related technology?
- How did NASA R&D contribute to the development of technology?
- How broad are the scope and range of expected applications?
- How significant are the near-term economic impacts?

B. TILT-ROTOR AIRCRAFT

The promise of being "one of the most significant developments in the history of powered flight" is how the V-22 Osprey tilt-rotor aircraft is described in the current Jane's *All the World's Aircraft.*[1] This aircraft has resulted from many years of tilt-rotor research, development, and testing by NASA Ames Research Center in conjunction with Bell Helicopter and the Army. Statements by former Ames directors C. A. Syvertson and H. Mark that "the Tilt-Rotor

[1] Jane's *All the World's Aircraft, 1987-88*, Jane's Publishing, Inc., London and New York, 1987, p. 43.

Project was the most significant accomplishment in Aeronautics at Ames in the last 20 years,"[2] further emphasize the importance of tilt-rotor technology and its potential benefits for the future. The goal of the development of tilt-rotor aircraft has been to combine some of the major attributes of helicopters and airplanes into a single aircraft. In joining the vertical takeoff and landing capability of helicopters with the higher speed, altitude, and range possibilities of an airplane, a highly versatile and useful aircraft results.

Work on various hybrid aircraft has been under way since the 1950s. As numerous technical problems have been solved and advances made, the tilt-rotor form of hybrid has had the greatest success in development and is the type nearest production. There are many variables involved, but it is possible that there could be commercial tilt-rotor service by the late 1990s, following the advent of military use in the early 1990s.

C. ELECTRO-EXPULSIVE DEICING

National Aeronautics and Space Administration scientist Leonard A. Haslim recently won NASA's 1988 Inventor of the Year Award for his Electro-Expulsive Separation System which, among a variety of possible uses, can be a surface deicer. This innovation can remove ice of thicknesses from mere frost to a one-inch glaze in less than a millisecond and requires only a thousandth of the power and one-tenth of the weight of existing systems to do so.[3]

Protecting aircraft surfaces from ice has been a major technological impediment to expanding the operational capabilities of modern high-performance aircraft into wider ranges of weather conditions. Advanced airfoil shapes and engine inlets are particularly sensitive to ice accumulation and may become limited in mission capabilities under icing conditions because of increased drag, reduced lift, and generally degraded performance.

Ice protection systems for aircraft take two basic approaches--either ice prevention or ice removal. A number of technologies have been applied, and NASA's Ames Research Center's new electro-expulsive deicer offers great potential for success.

Successful test results for the electro-expulsive deicer will bring benefits of improved performance in icing conditions and also expanded flying capabilities in a wider range of weather conditions. There also may be added protection

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[2] David D. Few, "A Perspective on 15 Years of Proof-of-Concept Aircraft Development and Flight Research at Ames-Moffett by the Rotorcraft and Powered-Lift Flight Projects Division, 1970-1985, NASA Reference Publication 1187, August 1987, p. 10.

[3] "Ames Invention Ices Top NASA Award," *NASA Tech Briefs*, June 1988, p. 34.

against rain erosion since the deicer system employs an erosion-resistant material for the bondable boot.[4] These benefits will extend not only to new aircraft but to existing models of many types because the system's flexibility, low power requirements, and light weight make it ideal for retrofitting aircraft that lack icing protection.

D. TUNNELING SENSORS

The scanning tunneling microscope (STM) is an instrument that "sees" the surfaces of solids atom by atom with a fine needlelike probe. The STM scans by moving its extremely sharp (just one atom wide at the tip) stylus over the surface of the sample, very near but not touching it. The application of voltage between the tip and the sample causes electrons to flow; this is the tunneling current (called this because the electrons appear to be digging a tunnel).

NASA's current development of tunneling sensors and new applications for these remarkable tiny supersensitive devices is opening a door to technologies that until recently were futuristic fantasies. These sensors can be accelerometers 100,000 times more sensitive than existing ones but at only a fraction of the cost, or they may someday be implants in a muscle stimulation and feedback system that would allow a paraplegic to walk.

Scanning tunneling spectroscopy research dealing with matters of intense scientific interest such as superconductivity also is taking place at NASA research centers. Both tunneling sensing and scanning tunneling spectroscopy are offspring of the STM.

E. COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) is a process of numerical simulation, modeling, and visualization for testing airflow patterns and their effects on aircraft, components, or other structures. It is a computer technique that gives researchers another means of investigating scientific phenomena in addition to traditional theoretical and experimental methods.

In computational fluid dynamics, the structure or design idea under investigation is computer-simulated, and extensive computations of various flow effects are made. The first step is to create a two- or three-dimensional grid in which the grid points (there may be hundreds of thousands) are the locations at which temperature, velocity, and pressure are calculated. The location and spacing of these points determine the complexity of the calculations and the accuracy of the results. In some cases, software engineers can spend more time designing the geometry of the grid than in solving for the flow.[5]

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[4] Haslim, "Electro-Expulsive Deicers for Rotorcraft," Research Description, NASA Ames Research Center, Moffett Field, California, p. 1.

[5] Jay C. Lowndes, "Arnold Engineering Expedites Use of Computational Fluid Dynamics," *Aviation Week and Space Technology*, September 1, 1986, p. 191.

The next step is to apply software codes to calculate the various flow effects. Many codes have been created and are available for use or adaptation, or a new code or codes may need to be developed to provide the most effective analysis for the particular situation. The advent of supercomputers enables calculations that would not be possible with less computer capacity. They also save much time and cost, reducing possible days of computing time to hours.[6]

The airflow data resulting from the computations allow evaluation of the design, which then may be reconfigured if necessary and the calculations gone through again until the design is deemed ready for further steps, such as subscale model building and experimental or wind tunnel testing. CFD provides baseline information against which further test data may be compared. The experimental or wind tunnel data may be used to validate the computer modeling, and adjustments may be made in the codes to make them more effective for a particular situation.

Computational fluid dynamics testing saves time and money in design by reducing trial and error in actual construction. It provides great quantities of data that can be displayed visually as well as numerically for greater ease in interpretation. Also, it can test for things that it otherwise might not be possible to test for in wind tunnel or actual flight testing. Advances in computational fluid dynamics, such as the work of Rai, are critical to the maintenance of U.S. technical leadership in the highly competitive aerospace market, according to an Ames official. The United States has a considerable lead in CFD over competitors in Europe and Japan because of NASA's early commitment to CFD research and the availability of superior facilities such as the Ames Numerical Aerodynamic Simulator system.[7]

F. COMPUTATIONAL CHEMISTRY

Progress in computational techniques in chemistry has been occurring as advances have taken place in aerodynamics and other areas. Theoretical chemists can calculate the properties of molecules and the reaction rates between molecules about as accurately as they can be measured experimentally. Simulation by computer adds the benefits of getting the information faster and at lower cost. Also, computer simulation may be the only way to obtain some results where experiments would be too dangerous or not even possible in principle.

NASA's Ames Research Center has led computational chemistry to the point where today molecular properties, chemical reaction rates, gas-solid interactions, and properties of materials can be predicted. Whereas previous calculations were valid only for single atoms, present methods are being used to accurately simulate gas/surface interactions involving 30 atoms and to predict

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[6] Lowndes, op. cit., p. 185.

[7] Richard G. O'Lone, "NASA Simulation Model Will Increase Precision Engine Flow Studies," *Aviation Week and Space Technology*, July 25, 1988, pp. 32-33.

interatomic forces in clusters as large as 65 atoms. In addition, the forces from these calculations are being used in the simulation of material properties containing up to 10,000 interacting atoms.[8]

An early example of the advantage of computational methods comes from Battelle Columbus Laboratories. Researchers were to select, from a group of closely related organic dye molecules, the ones that might be the most promising for synthesis and characterization as possible materials for solar energy collectors. With computer techniques, the chemists were able to select the desirable molecules in about one-hundredth the time it would have taken with experimentation.[9]

While great progress has been made by NASA in computational chemistry, the major impact has yet to be realized. It has the potential to enable better understanding and design of new, stronger, lightweight materials for aerospace use and improved catalysts for substantially increased fuel efficiency.[10] Future improvements in supercomputers and computational developments in many areas will continue to expand applications of simulation and modeling techniques and the practical benefits that will result.

G. PROTEIN CRYSTAL GROWTH

Protein crystal growth is an area of research and potential productivity that has flourished with NASA space programs. Even though crystal growth can be accomplished on Earth, it can be done much faster and better in space. NASA's encouragement of commercial use and development of space in the last few years, especially with the establishment of Centers for the Commercial Development of Space, furthered protein crystal growth experiments by pharmaceutical companies as well as by university researchers.

Protein crystal growth is primarily a pharmaceutical and medical research activity that may be a key to developing powerful new medicines and treatments through bioengineering. In bioengineering, the molecular structure of drugs is tailored specifically to work with or against the atomic structures of protein molecules in the body. There are about 250,000 proteins that could be studied, and many are critical to life and the disease mechanisms that threaten life. Essential to this study is the need to understand in detail the atomic structure of the proteins to be attacked or treated, and this structure may be examined in the crystalline form of the protein. Earth's gravity makes it difficult to grow large enough crystals with few enough defects for effective

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[8] Ames Research Center staff, "Some Innovations and Accomplishments of Ames Research Center Since the Inception," NASA Technical Memorandum 88348, 1987, p. 4.

[9] Arthur L. Robinson, "An 'NRCC' for Industrial Chemists?" *Science*, September 26, 1980, p. 1506.

[10] Ames Research Center Staff, op. cit., p. 5.

atomic characterization, but the microgravity of space makes it possible to grow crystals large enough to allow determination back on Earth of their three-dimensional atomic structure. (In one experiment one type of protein grew crystals 30 times larger than possible on Earth, and another type grew 1,000 times larger.) With knowledge of the atomic form, the molecular structure of a medicine, for example, then can be engineered.[11]

One indication of the importance of the field of protein crystal growth is that by 1985 it had resulted in eight Nobel prizes.[12]

The benefits will be both medical and commercial as powerful disease-fighting drugs and treatments are developed, generating billions of dollars of pharmaceutical business. Also, the use of space for protein crystal growth would relieve a severe research bottleneck that exists in this field of study.

Significant applications will be for new cancer drugs, DNA research, gene crystallization, treatment of high blood pressure and rejection of transplant organs, and for herbicide development and other areas of organic chemistry.

H. TUNABLE SOLID-STATE LASER

A tunable solid-state laser is a type of laser which can have the frequency of its light adjusted and which has a solid (not liquid or gaseous) lasing substance.

Since the operation of the original ruby laser in the early 1960s, scientists have been searching for other solid-state laser materials that, instead of being limited to one wavelength, could be continuously tuned across a significant range of the electromagnetic spectrum (EM). In the mid-1970s, research activity in this area picked up with a development program at Allied Corporation on alexandrite ($Cr{:}BeAl_2O_4$) and at Massachusetts Institute of Technology Lincoln Laboratory on nickel, cobalt, and titanium ions in hosts such as MgF_2 and Al_2O_3. In the 1980s greater national interest in the development of tunable solid-state lasers emerged, and also in the development of semiconductor laser arrays, in which millions of diodes are stacked in linear bars, as radiation sources for optically pumping the solid-state laser materials.

At an international conference on tunable solid-state lasers in 1984, it was recognized that tunable solid-state lasers were critical to future remote sensing applications. Representatives from industry, academia, and government urged NASA to develop a strong program focused on a new tunable material, titanium-doped sapphire ($Ti{:}Al_2O_3$), recently discovered by Peter Moulton at MIT. NASA's Office of Aeronautics and Space Technology (OAST)

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[11] Craig Covault, "Shuttle Crystal Growth Tests Could Advance Cancer Research," *Aviation Week and Space Technology*, February 25, 1985, p. 18.

[12] Ibid., p. 20.

and Langley Research Center accepted the challenge and established the goal of having an all solid-state laser technology based on titanium-doped sapphire demonstrated for applications on Earth Observing System (Eos) by 1989.

NASA has realized its goal and is ready to demonstrate titanium-doped sapphire solid-state laser technology for applications on Eos and research aircraft. By 1990, all relevant designs will have been tested in laboratory prototypes for the two experiments NASA proposed to the Eos.

For future development, NASA wants to extend tunable solid-state laser technology into farther ranges of the electromagnetic spectrum. In doing so, other important trace gases in the earth's troposphere, such as carbon monoxide and methane, can be measured. These are important to our future understanding of the greenhouse effect and the earth's radiation budget.

L ADVANCED TURBOPROP

Advanced turboprop (ATP) is a new development in aircraft propulsion for air transports that operate in short- to medium-range markets. It reintroduces propellers, but with new technology, and creates an improved propulsion system that has the fuel efficiency of propeller engines while maintaining speed and altitude capabilities of currently used jets.

Advanced turboprop research was under way in the 1970s and early 1980s. During congressional hearings on NASA's fiscal 1982 budget, strong industry support surfaced for accelerating ATP programs to demonstrate technology readiness by the mid-1980s so that airframe and engine manufacturers could produce a commercial aircraft by 1990. Even though some of the relevant designs had been known for some time, they could not be fulfilled because the necessary technology did not yet exist. The 1980s brought development of high-speed computers, sophisticated engineering software, and advanced composite materials that provided the essential analytical capabilities and construction materials.

NASA has been involved all along the way with advanced turboprop development. Research and testing have been carried out at various NASA facilities, including the Ames, Lewis, and Langley Research Centers.

NASA's Propfan Test Assessment (PTA) program has been a joint effort with several companies and just earlier this year completed its flight testing of a single-rotation ultrahigh bypass ratio power plant. In this program a 9-foot diameter propfan developed for Lewis by Hamilton Standard Division of United Technologies was tested. Also part of the unit was a drive system of modified existing engine and gearbox by General Motors' Allison Gas Turbine Division. Rohr Industries Inc. created a new engine nacelle design. The engine was mounted as an "extra engine" on the wing of a twin jet Gulfstream II light transport modified by Lockheed-Georgia Company.

The series of flight tests were conducted by Lockheed, focusing on propfan integrity and acoustic characteristics, the two remaining technical issues that could not be adequately investigated at model scale. Additionally, Lockheed-California conducted ground tests for new concepts for cabin noise reduction.

Further, NASA technology research and funding have assisted most, if not all, of the turboprop research done by American aeronautical companies.

Advanced turboprop engines will bring the benefits of significant reduction in fuel consumption and cost and noise. Moreover, much fundamental research has taken place. There have been developments in computers, software, computational fluid dynamics, and advanced composite materials. These advances have implications that will spill over into numerous other areas. Finally, some believe that advanced turboprop will be as large an improvement over current aircraft as were jet transports in 1958 and high-bypass engines in the 1960s. According to Joseph F. Sutter, executive vice president of Boeing, "This is the next big step."

CONCLUSIONS

The findings of Midwest Research Institute are that the economic impact of R&D expenditures is substantial. We have also found NASA's role in the economic and technological growth of the United States to be substantial as illustrated in the two case studies: digital communications and civil aeronautics performance and efficiency. In addition, it has been clear to the MRI research team that NASA has also had an impact in a broad range of technological areas. As was stated earlier, during the course of conducting the study, some 250 important NASA technologies were reviewed, and there are literally thousands of examples where NASA's role made the difference in technological progress.

NASA's role has been important not only in the past, but indications are that the breadth and depth of NASA expertise will continue to contribute to technological growth in the future, not only in the United States but in worldwide markets as well. Many of the technologies that MRI has reviewed have been picked up by foreign companies and successfully commercialized. The extent of foreign acquisition and commercialization is outside the scope of this study but nonetheless clearly illustrates the usefulness and productiveness of NASA technology worldwide.

This Executive Report has sought to summarize key points and findings in the fuller MRI study. For further reading, additional volumes of this study include:

- Volume II—Economic Impact of R&D Expenditures

- Volume III—Technology Case Studies

    Digital Communications

    Civil Aeronautics Performance and Efficiency

    Future Technology Areas

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